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(54) **METHOD AND SYSTEM FOR MULTI-PHASE FLOW MEASUREMENT**

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G01M 3/00 (2006.01)
G01F 1/74 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***G01F 1/74*** (2013.01); ***E21B 47/065*** (2013.01); ***E21B 47/123*** (2013.01); ***G01F 1/662*** (2013.01);

(Continued)

(58) **Field of Classification Search**

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(Continued)

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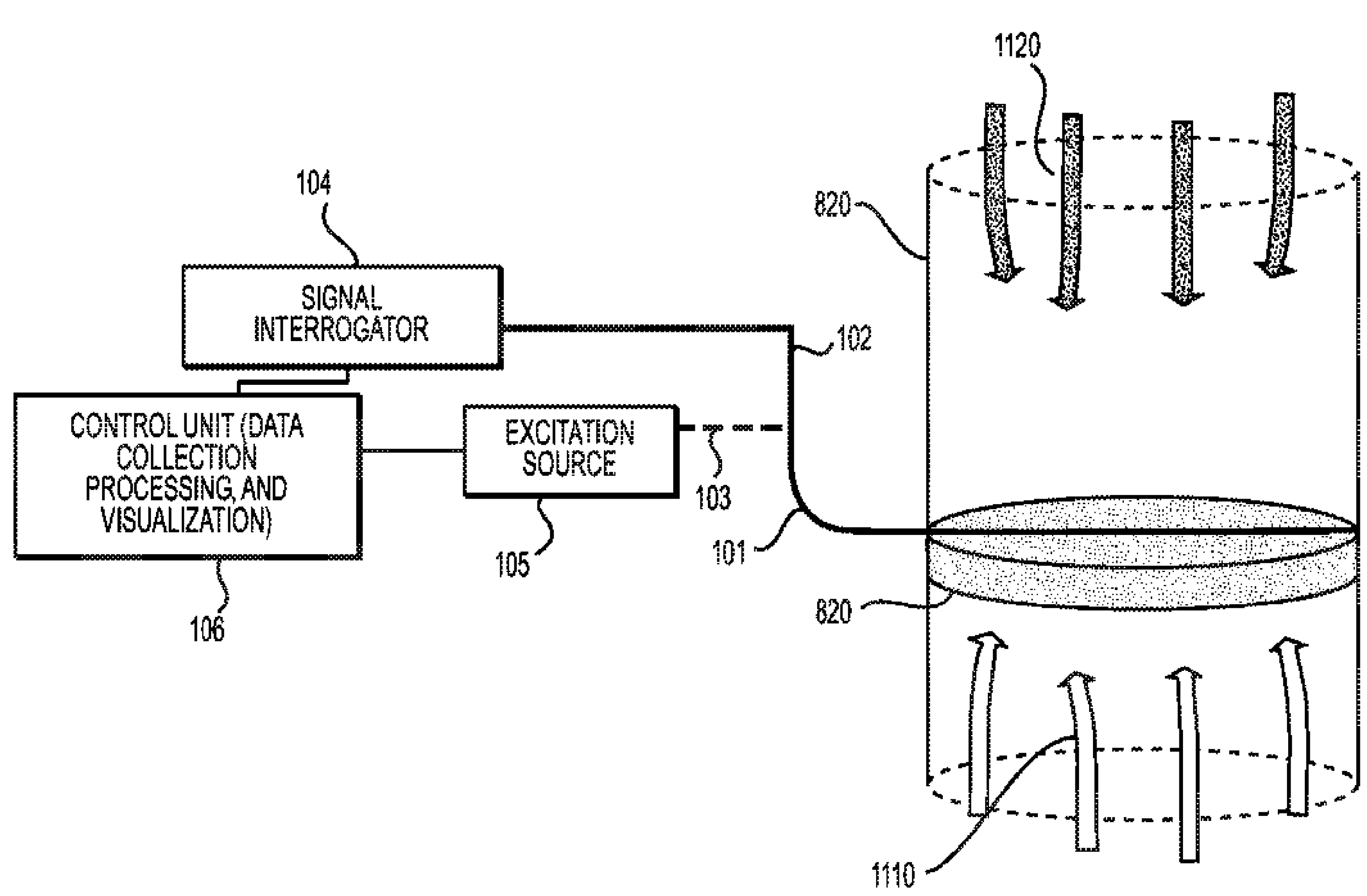
(57) **ABSTRACT**

Systems and methods for detecting a condition of multi-phase flow through a component with a first sensing cable having a first sensor location and aligned with a heating element and a second sensing cable having a second sensing location a predetermined distance from the first sensing location. A heat pulse is propagated through the heating element. A first temperature profile at the first sensing location and a second temperature profile at the second sensing location, each corresponding to the heat pulse, are measured over time. A flow velocity is determined by correlating the first temperature profile with the second temperature profile. A condition of flow of the media is detected by determining a phase of at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

26 Claims, 13 Drawing Sheets



(51) **Int. Cl.**

G01K 11/32	(2006.01)
G01F 1/684	(2006.01)
E21B 47/06	(2012.01)
E21B 47/12	(2012.01)
G01F 1/66	(2006.01)
G01F 1/704	(2006.01)

(52) **U.S. Cl.**
CPC ***G01F 1/684*** (2013.01); ***G01K 11/3206*** (2013.01); *G01F 1/7044* (2013.01)

(58) **Field of Classification Search**
USPC 73/40.5
See application file for complete search history.

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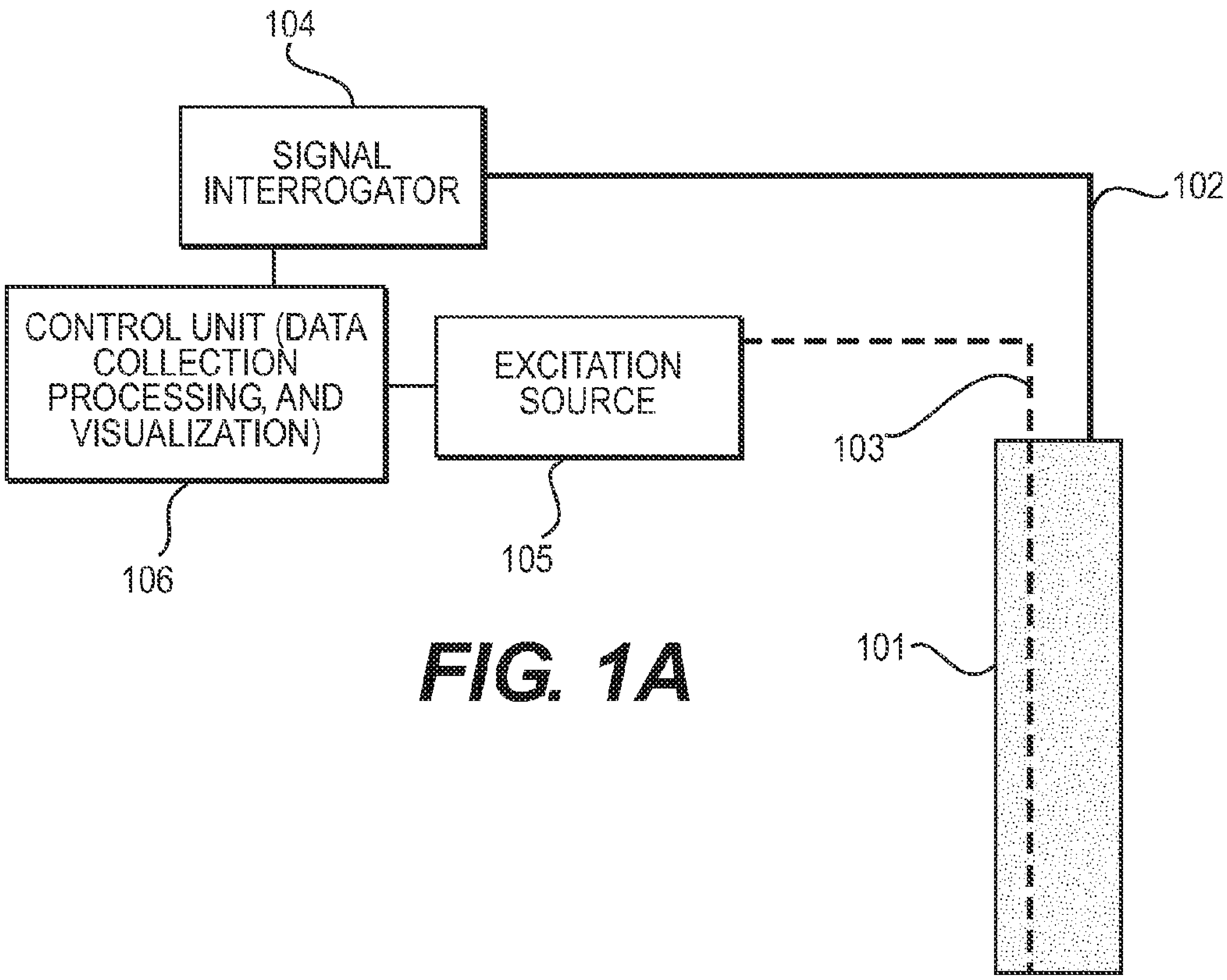

FIG. 1A

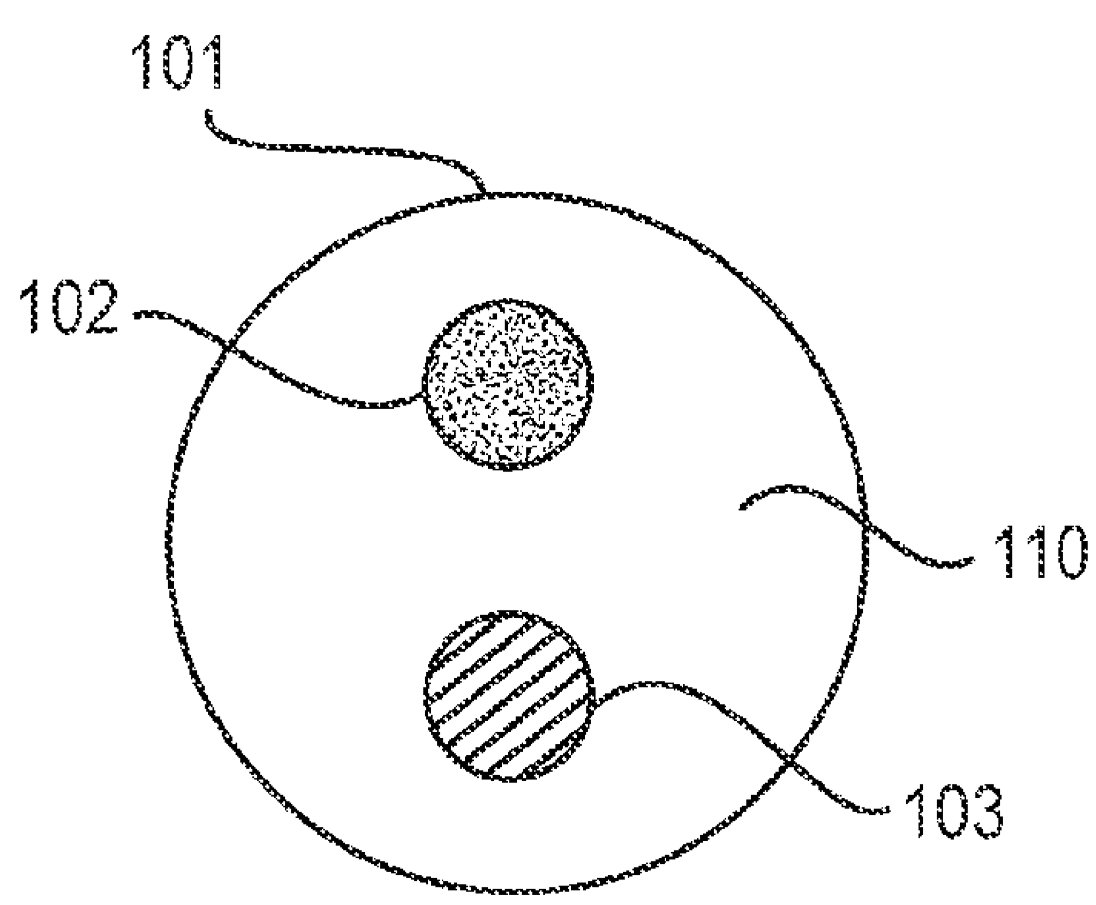

FIG. 1B

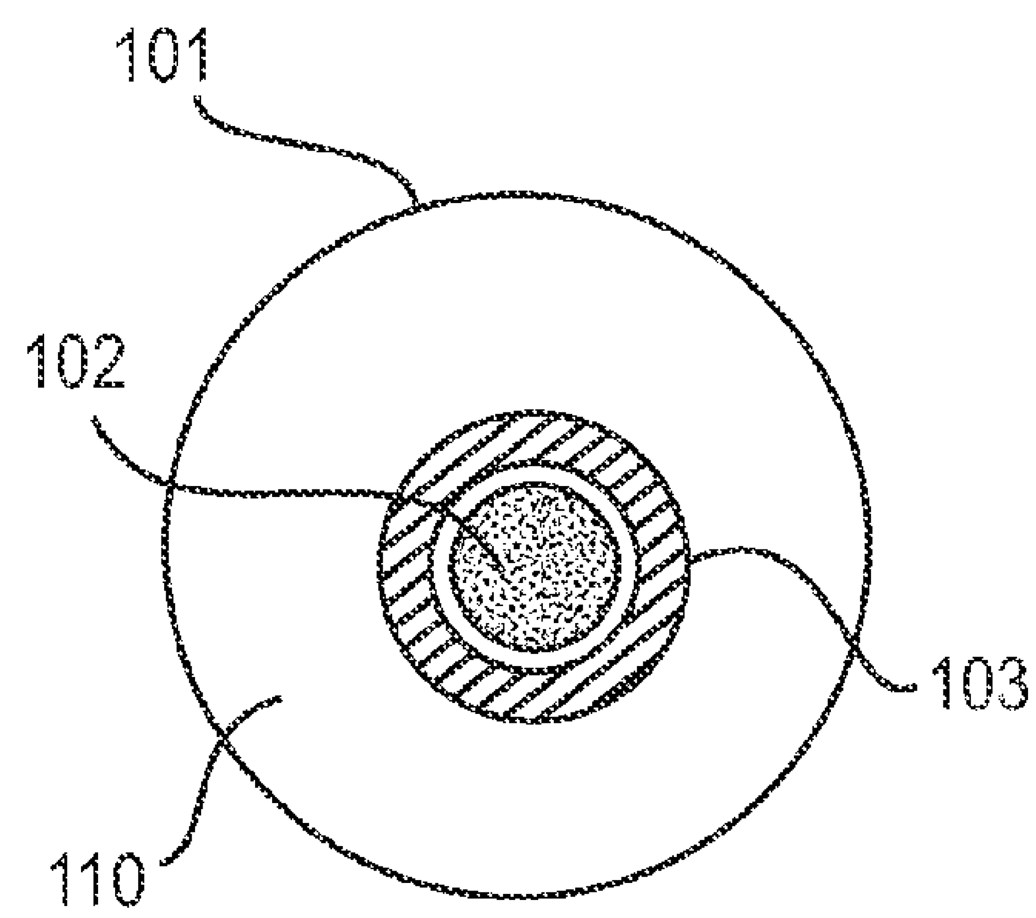

FIG. 1C

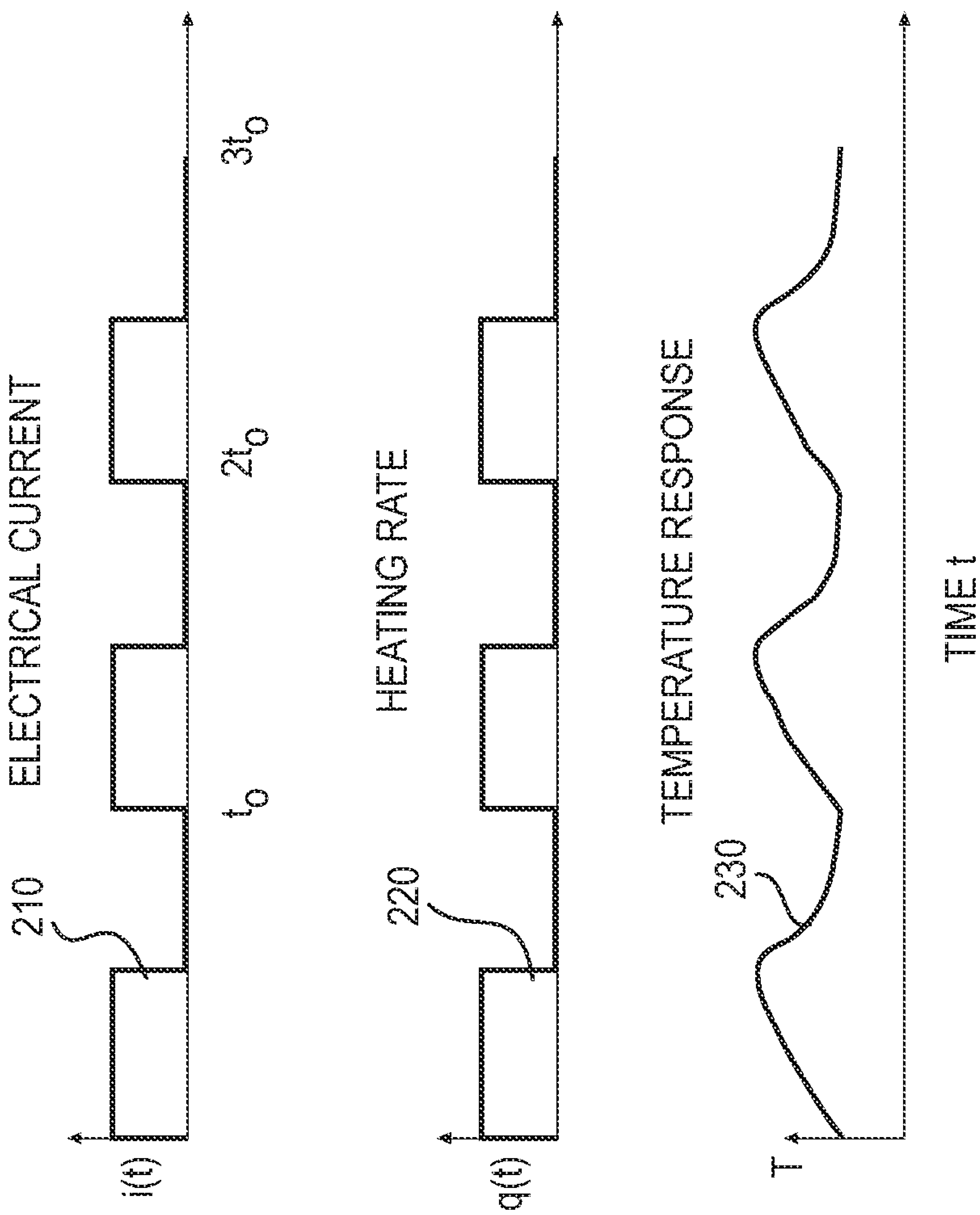
ELECTRICAL CURRENT
i(t)
210
t_o
$2t_o$
$3t_o$
HEATING RATE
q(t)
220
TEMPERATURE RESPONSE
T
230
TIME t

FIG. 2

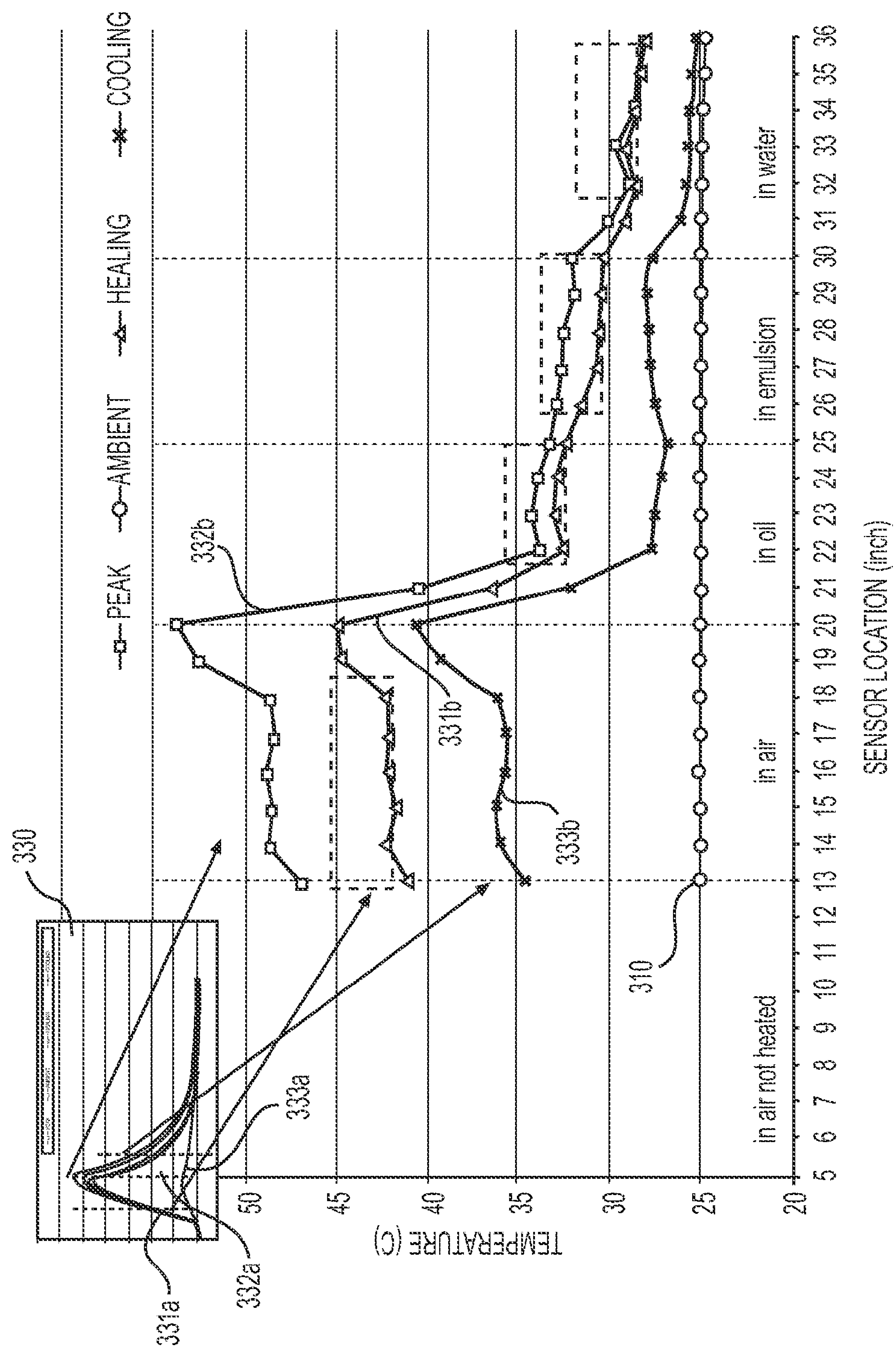
PEAK
AMBIENT
HEALING
COOLING
TEMPERATURE (C)
SENSOR LOCATION (inch)
in air not heated
in air
in oil
in emulsion
in water
330
331a
332a
333a
331b
332b
333b
310

FIG. 3

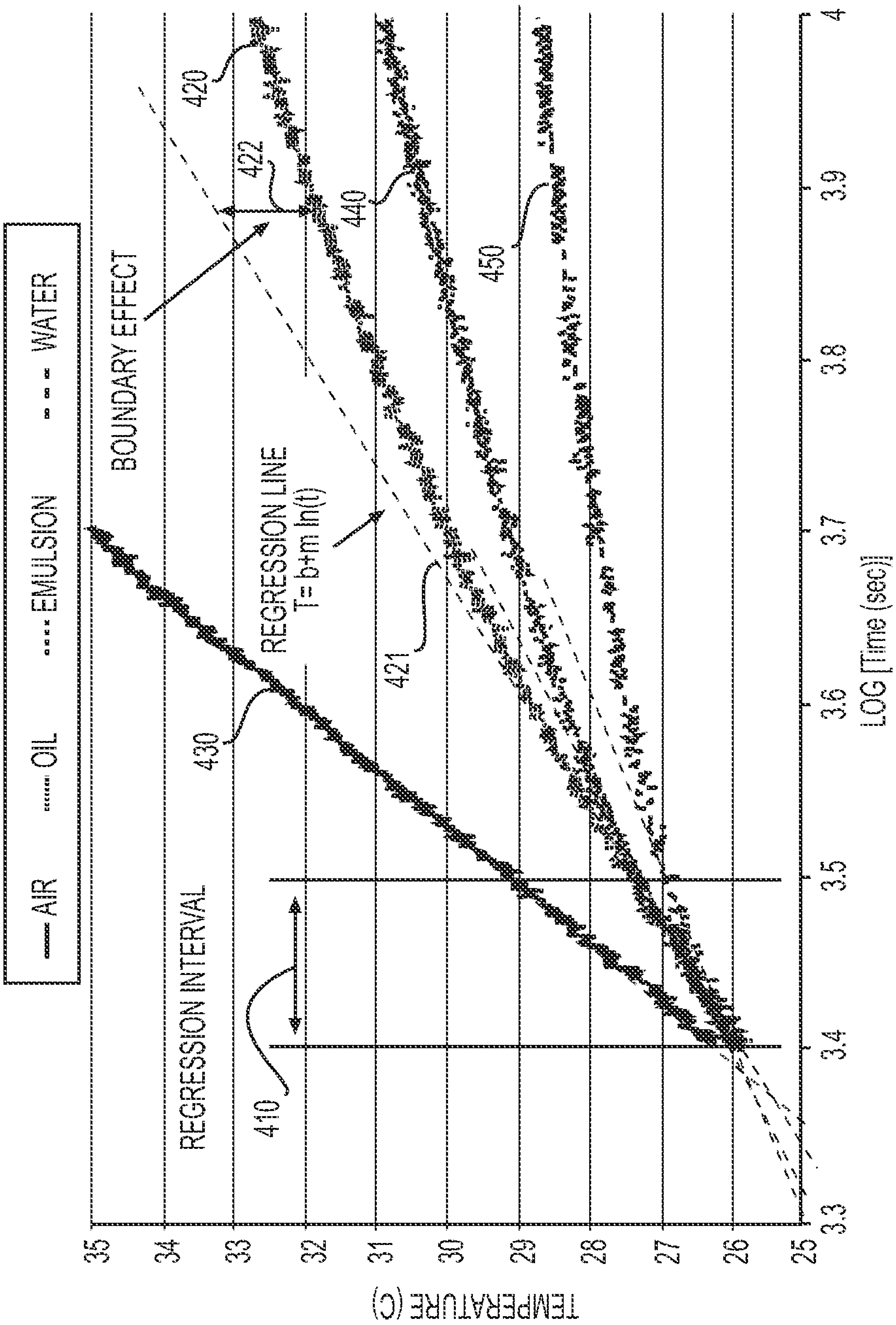
AIR
OIL
EMULSION
WATER
BOUNDARY EFFECT
REGRESSION LINE
T= b+m ln(t)
REGRESSION INTERVAL
410
420
421
422
430
440
450
TEMPERATURE (C)
35
34
33
32
31
30
29
28
27
26
25
LOG [Time (sec)]
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4

FIG. 4A

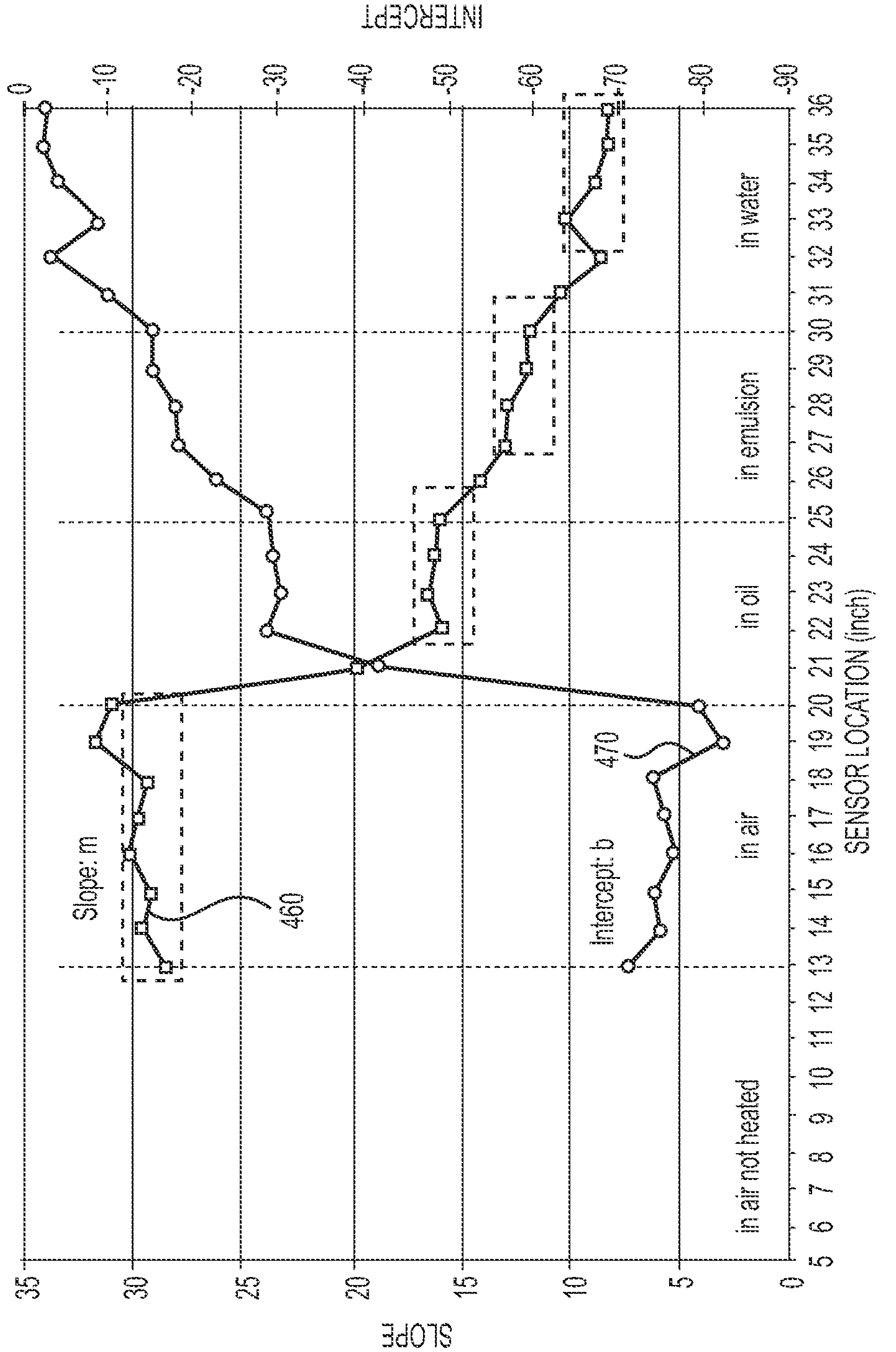
INTERCEPT
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
SLOPE
35
30
25
20
15
10
5
0
SENSOR LOCATION (inch)
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
Slope: m
460
Intercept: b
470
in air not heated
in air
in oil
in emulsion
in water

FIG. 4B

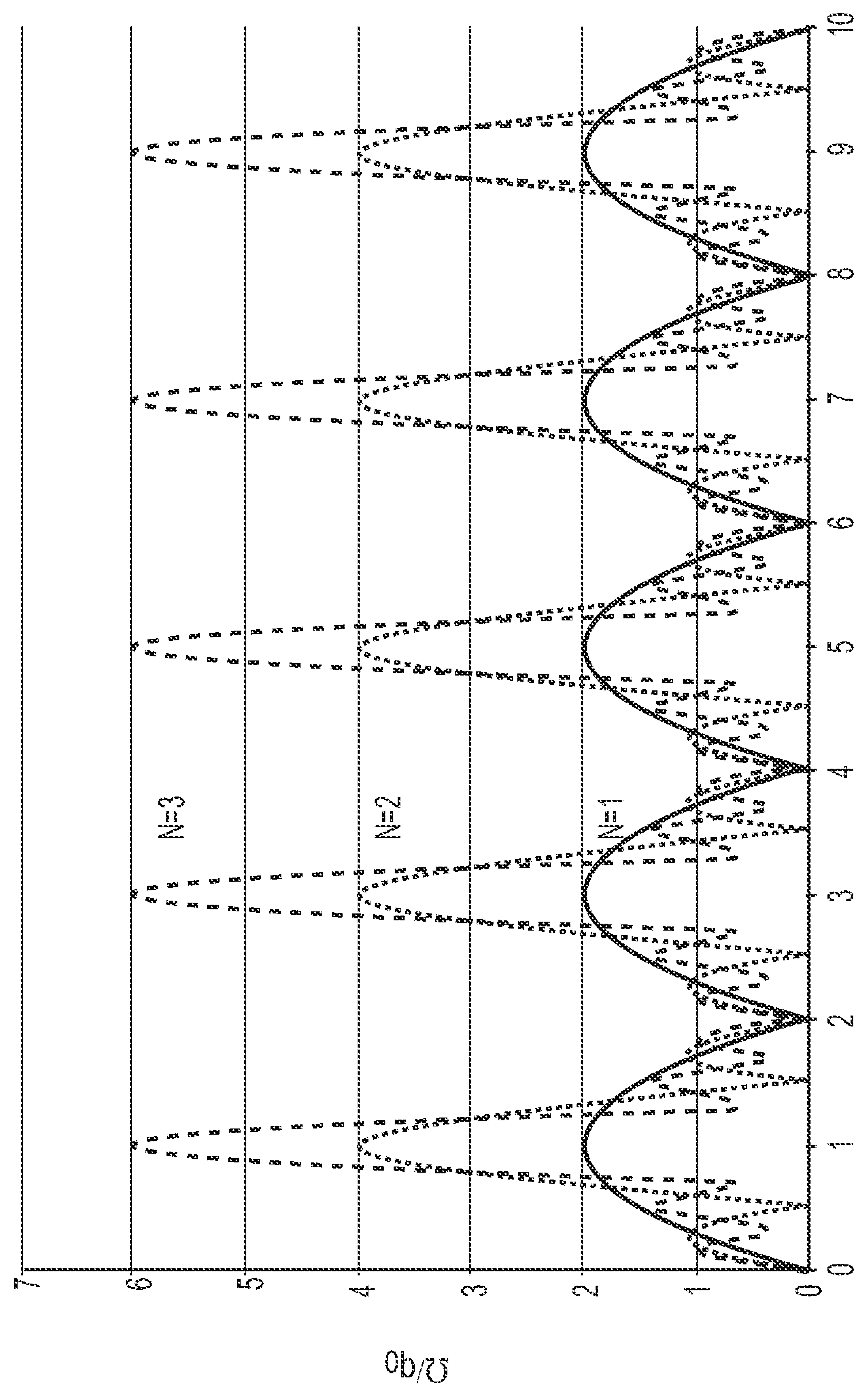

FIG. 5A

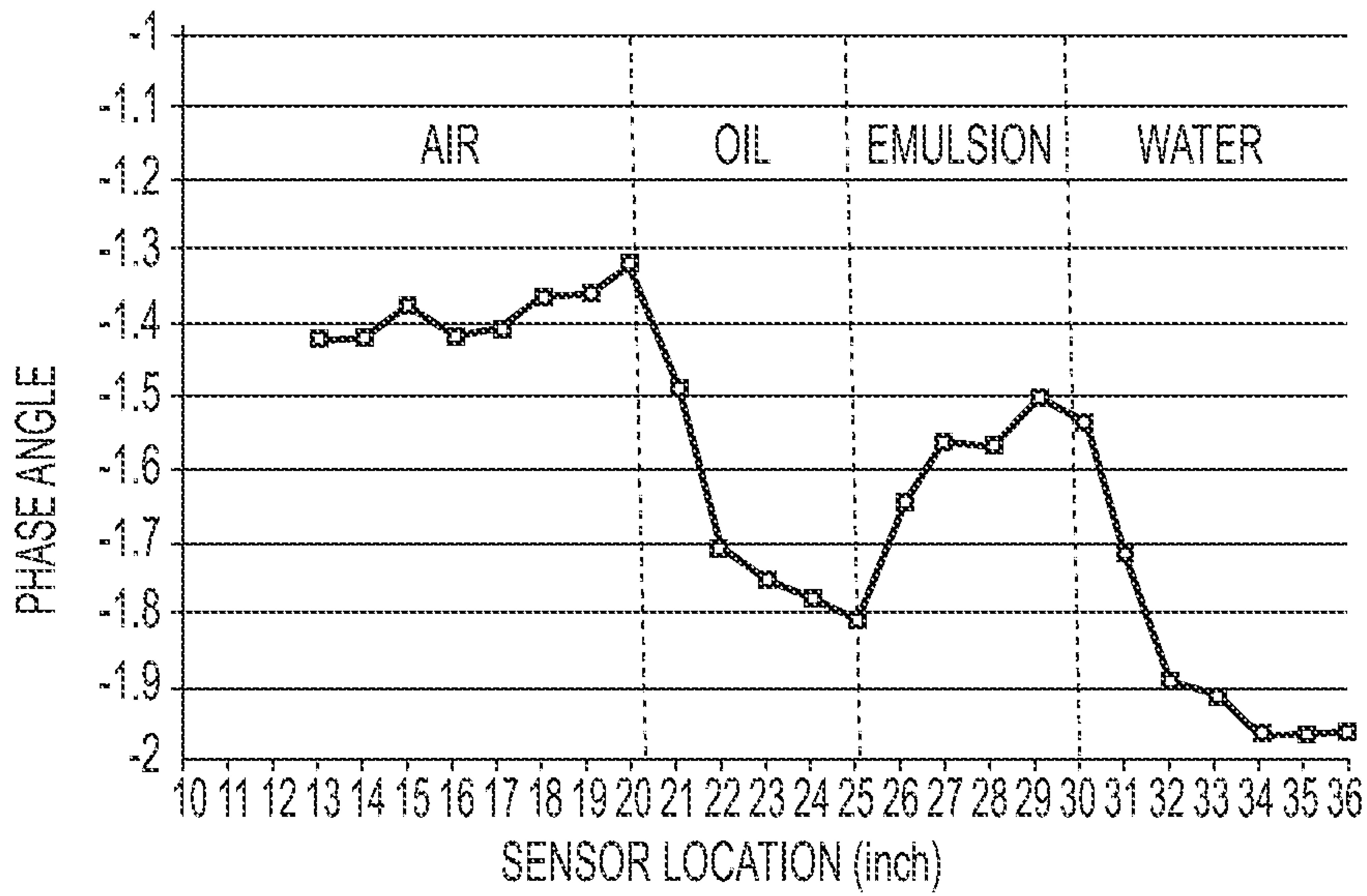
AIR
OIL
EMULSION
WATER
PHASE ANGLE
-1
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
SENSOR LOCATION (inch)

FIG. 5B

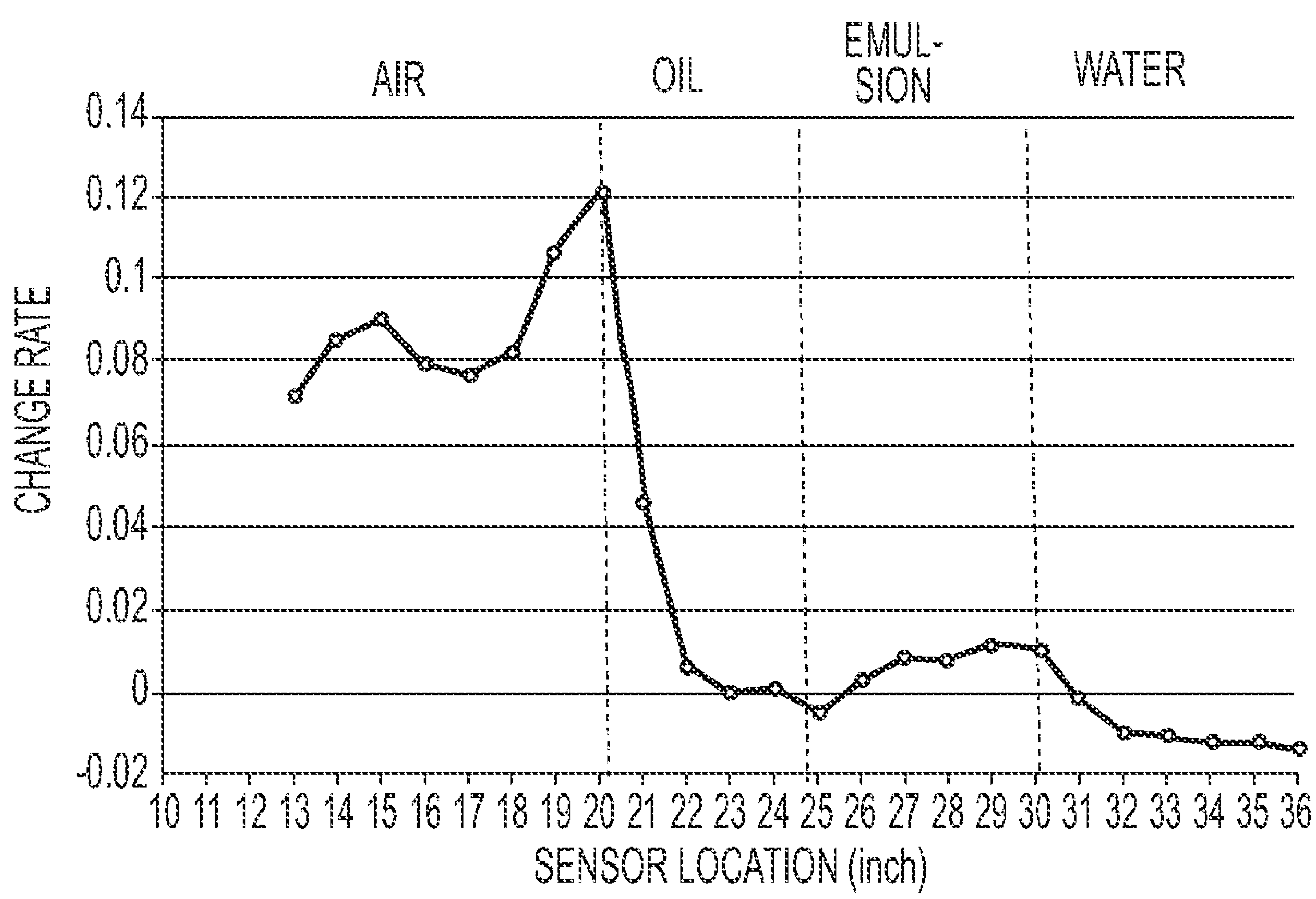
AIR
OIL
EMUL-
SION
WATER
CHANGE RATE
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
SENSOR LOCATION (inch)

FIG. 5C

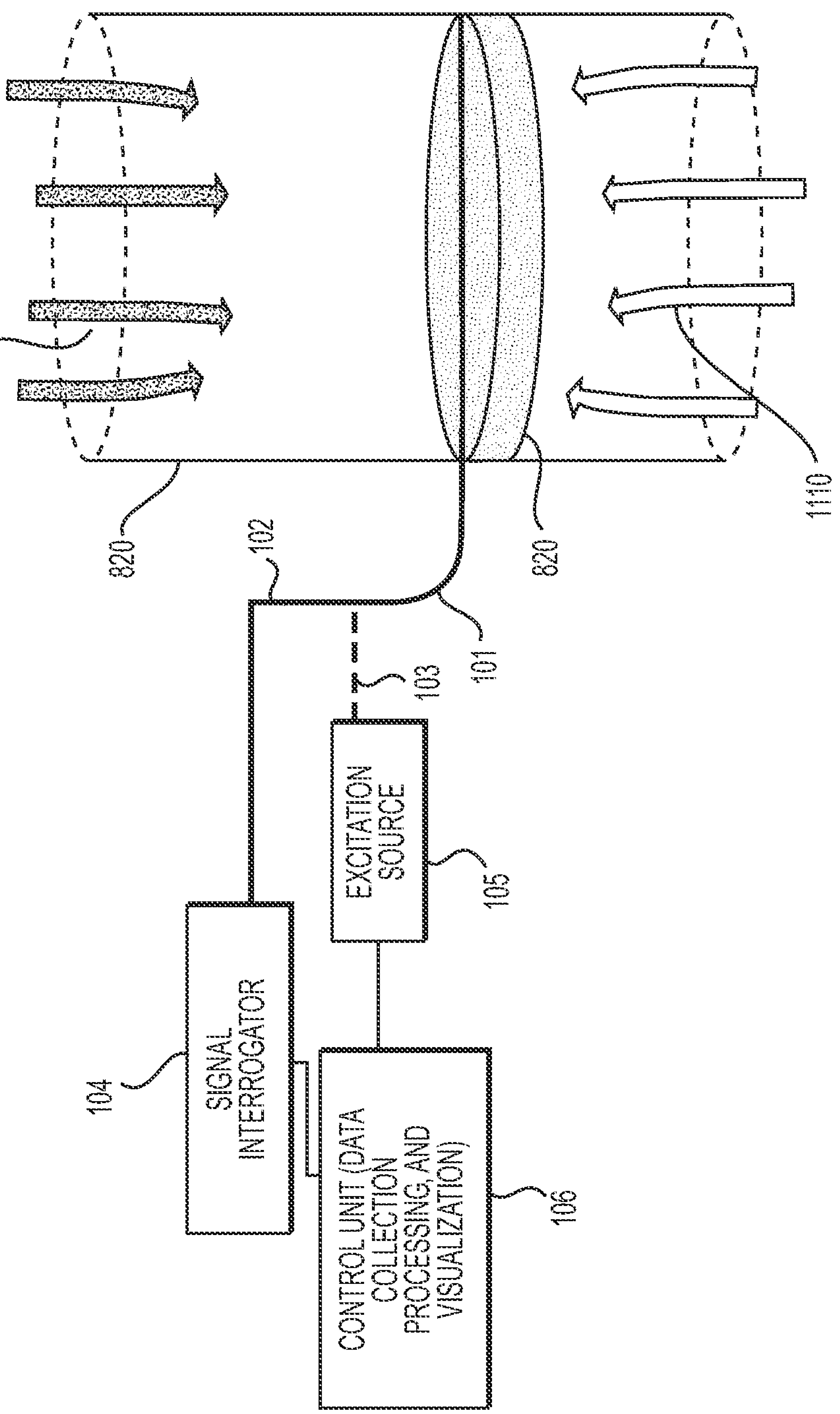
1120
820
102
101
103
820
1110
EXCITATION SOURCE
105
SIGNAL INTERROGATOR
104
CONTROL UNIT (DATA COLLECTION PROCESSING, AND VISUALIZATION)
106

FIG. 6

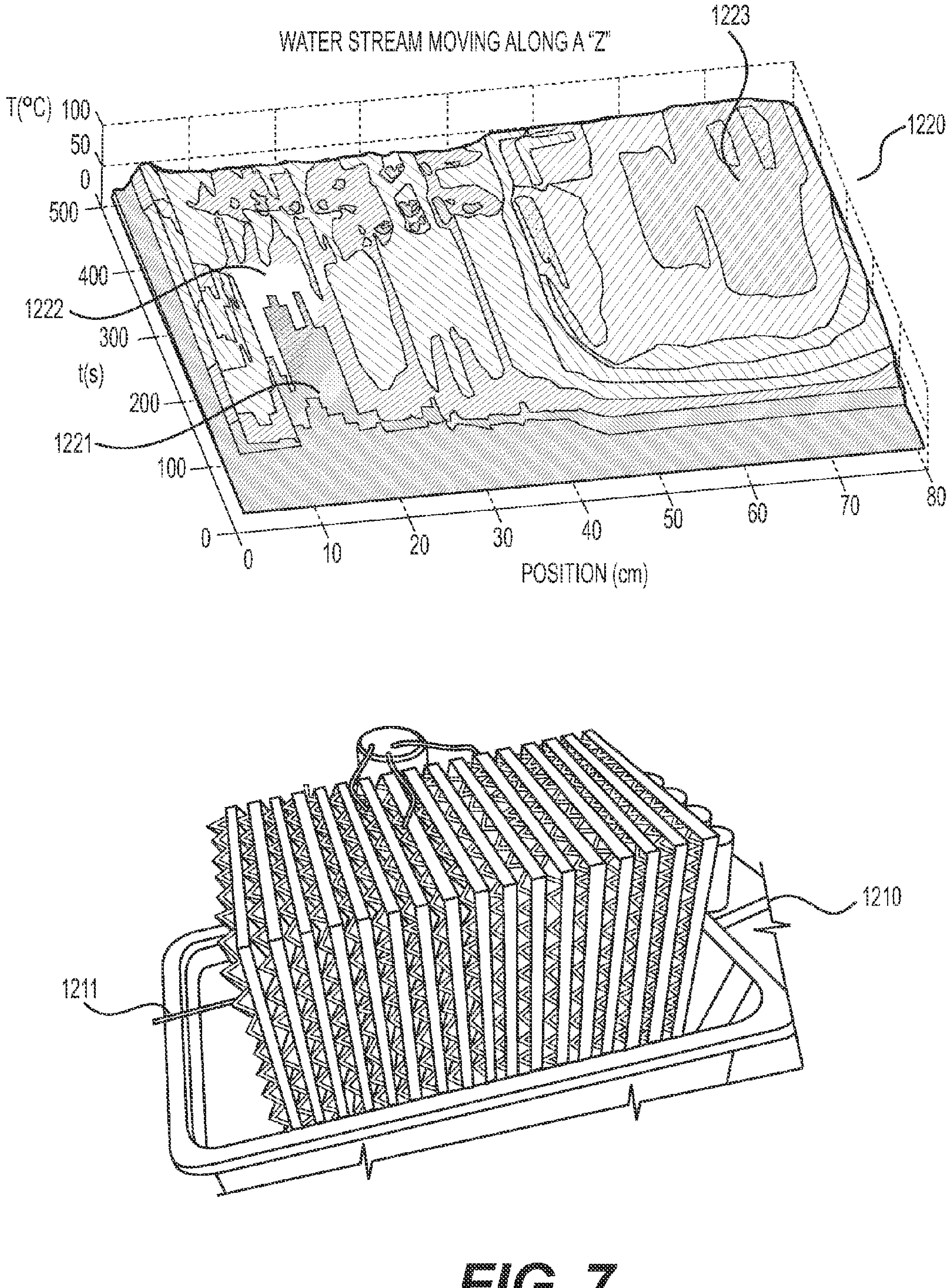
WATER STREAM MOVING ALONG A "Z"
1223
1220
T(°C) 100
50
0
500
400
300
200
100
0
t(s)
1222
1221
0
10
20
30
40
50
60
70
80
POSITION (cm)
1210
1211

FIG. 7

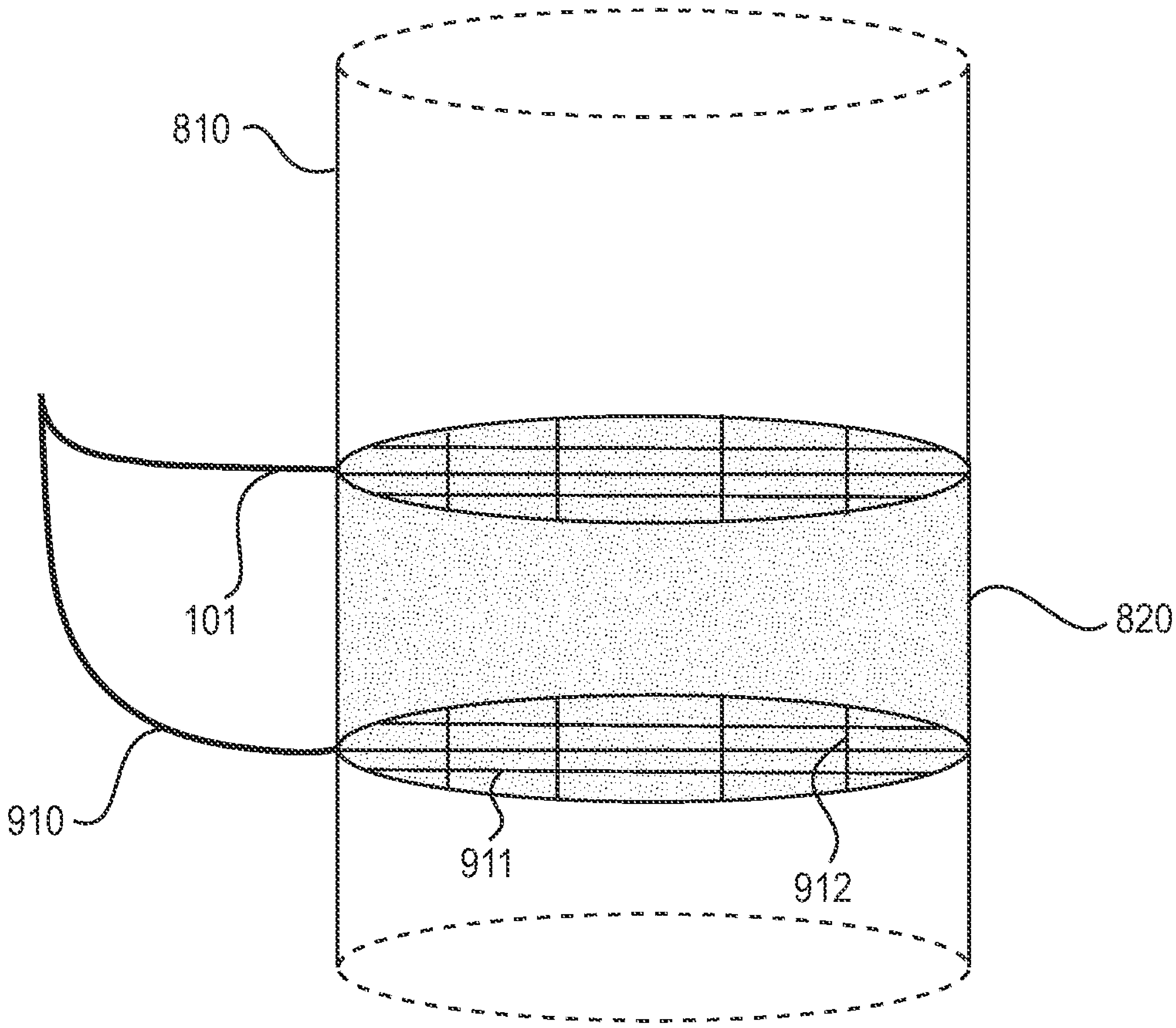

FIG. 8

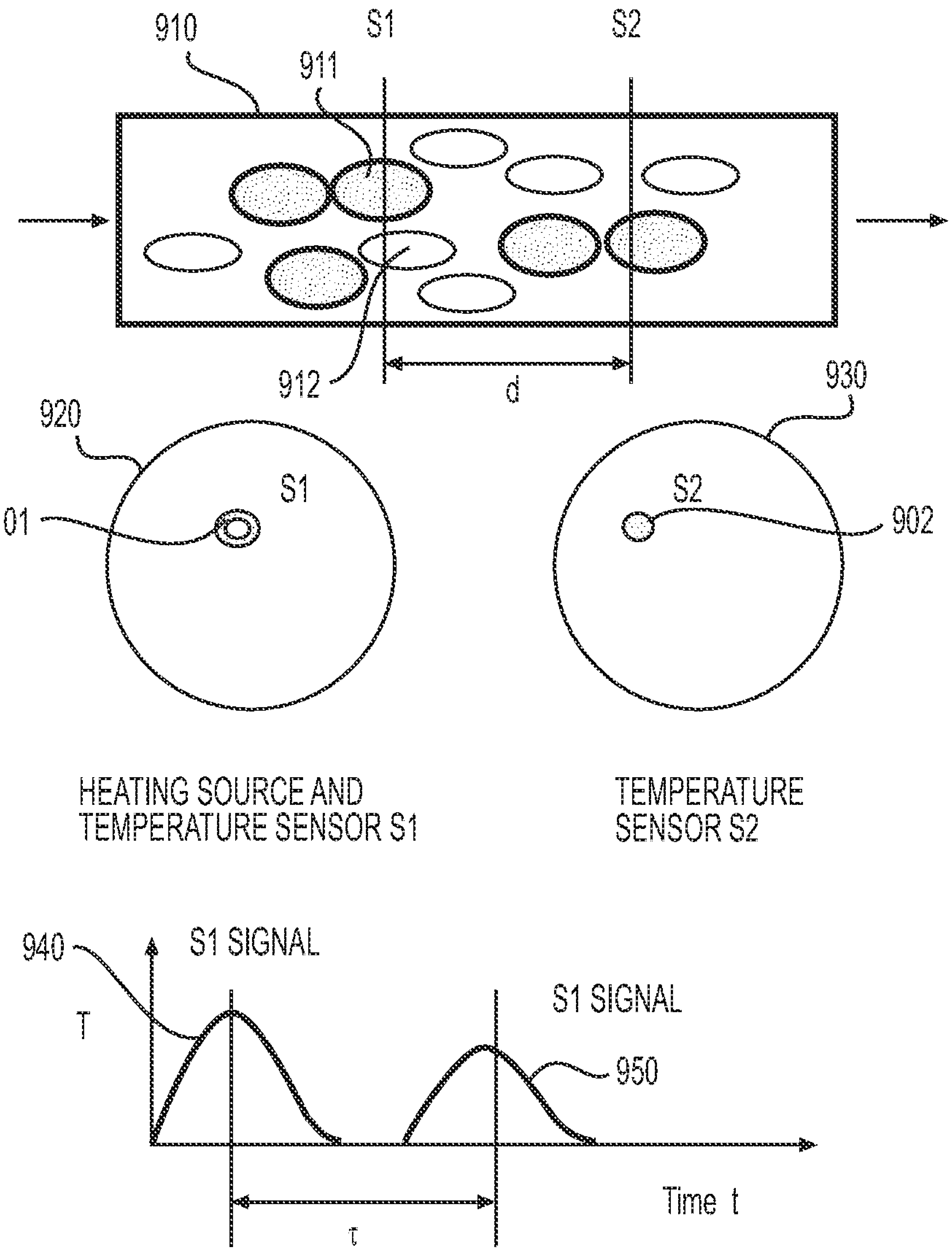
910
S1
S2
911
912
d
920
930
S1
S2
101
902
HEATING SOURCE AND TEMPERATURE SENSOR S1
TEMPERATURE SENSOR S2
940
S1 SIGNAL
T
S1 SIGNAL
950
τ
Time t

FIG. 9

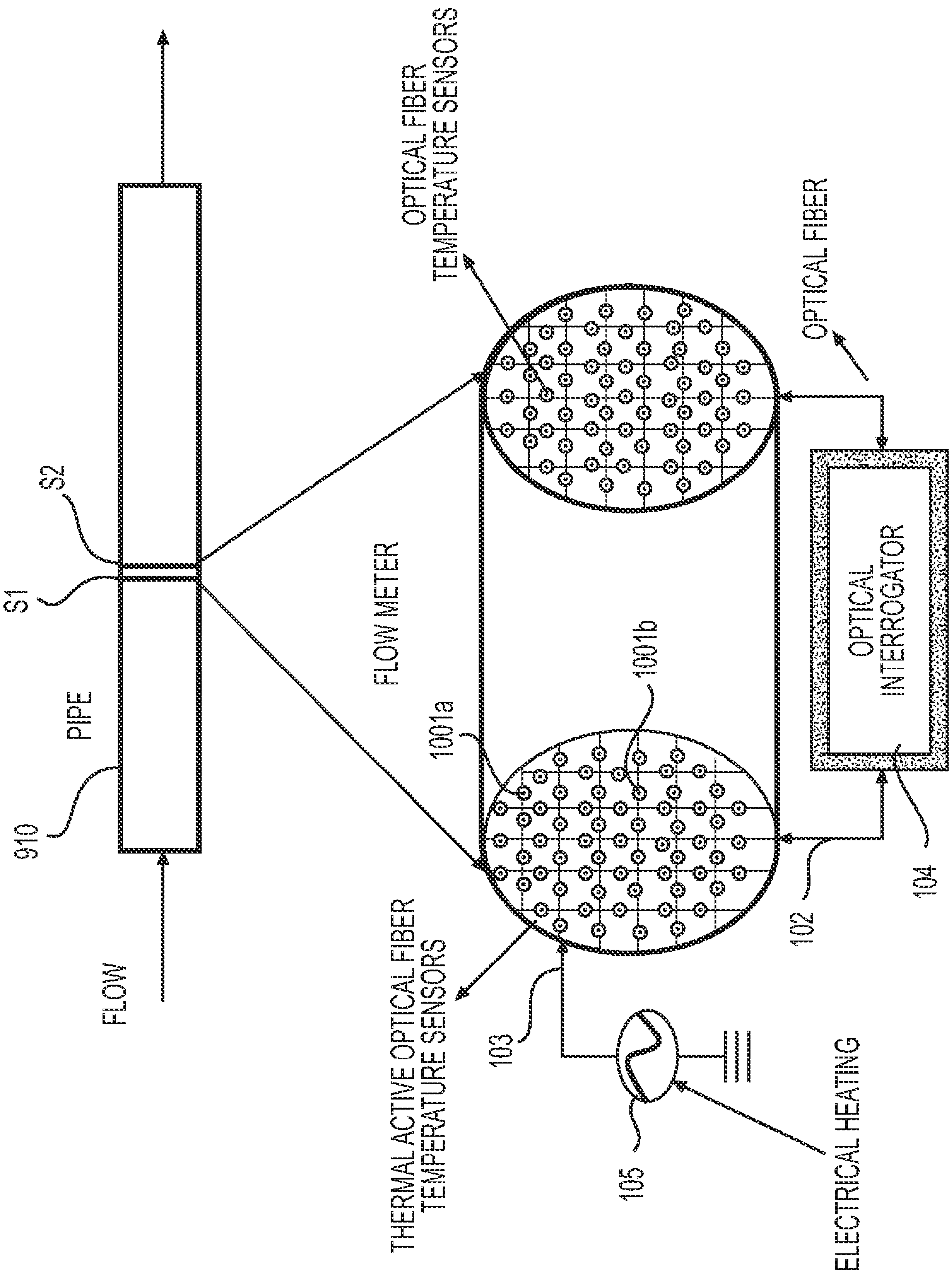
OPTICAL FIBER
TEMPERATURE SENSORS
OPTICAL FIBER
S2
S1
PIPE
910
FLOW
FLOW METER
1001a
1001b
OPTICAL
INTERROGATOR
THERMAL ACTIVE OPTICAL FIBER
TEMPERATURE SENSORS
103
102
104
105
ELECTRICAL HEATING

FIG. 10

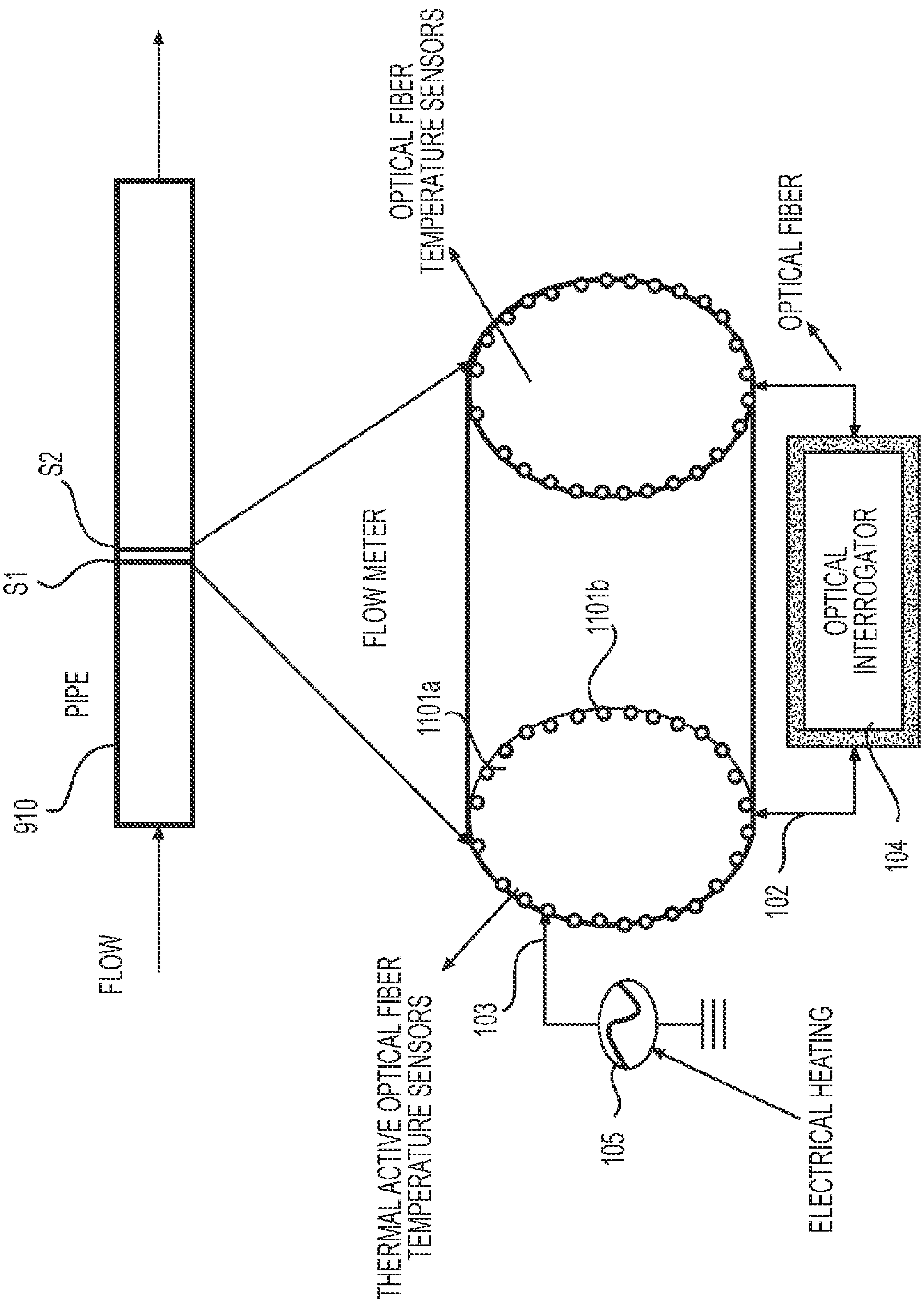
FLOW
910
PIPE
S1
S2
FLOW METER
OPTICAL FIBER TEMPERATURE SENSORS
1101a
1101b
THERMAL ACTIVE OPTICAL FIBER TEMPERATURE SENSORS
103
105
ELECTRICAL HEATING
102
OPTICAL FIBER
OPTICAL INTERROGATOR
104

FIG. 11

METHOD AND SYSTEM FOR MULTI-PHASE FLOW MEASUREMENT

CROSS REFERENCE TO RELATED APPLICATIONS

This application relates and claims priority to U.S. Provisional Patent Application No. 61/919,870, filed on Dec. 23, 2013.

BACKGROUND

Field

The presently disclosed subject matter relates to methods and systems for determining the flow distribution of a fluid through a component. More particularly, the presently disclosed subject matter relates to measuring multi-phase flow in a pipe.

Description of Related Art

Components of certain equipment, such as that used in the petroleum and petrochemical industry, which includes the exploration, production, refining, manufacture, supply, transport, formulation or blending of petroleum, petrochemicals, or the direct compounds thereof, are often monitored to maintain reliable operation. However, such components can involve harsh conditions, such as high temperature, high pressure, and/or a corrosive environment, making it difficult or costly to obtain reliable measurements.

Determining a condition of multi-phase flow can facilitate the metering of production from a gas or oil well, identification of irregular flow in a pipe in a refinery or chemical planet, determine the corrosion environment in a pipeline, and more generally to measure phase in a pipe flowing system.

Conventional techniques for measuring multi-phase flow include meter by a separator. For example, media flowing through a pipe can be directed to a separator which can, for example, separate the media (e.g., vapor, water, and oil) in a tank. The fraction of each medium can thus be determined. A separator, however, can be bulky and measurement typically must be accomplished offline and thus cannot be used for real time control. Additionally, conventional techniques for measuring multi-phase flow can include combining an average flow rate (e.g., measured using a venture flow device or a turbine placed within the flow) and an average phase measurement (e.g., measured using an acoustic system). Such techniques, however, provide only limited information about multi-phase flow.

Certain radiation-based approaches have also been proposed. For example, nuclear magnetic resonance imaging techniques can be used to image the flow in a small pipes, but cannot be used for lager pipes. Other radiation-based approaches, such as X-ray and gamma-ray imaging and electrical tomography can achieve only limited resolution and can be inadequate for many application.

Accordingly, there is a continued need for improved techniques for detecting a condition of multi-phase flow through a component.

SUMMARY OF THE INVENTION

The purpose and advantages of the disclosed subject matter will be set forth in and apparent from the description that follows, as well as will be learned by practice of the disclosed subject matter. Additional advantages of the disclosed subject matter will be realized and attained by the methods and systems particularly pointed out in the written description and claims hereof, as well as from the appended drawings. To achieve these and other advantages and in accordance with the purpose of the disclosed subject matter, as embodied and broadly described, the disclosed subject matter includes systems and methods for determining the flow distribution of a fluid through a component.

In accordance with one aspect of the disclosed subject matter, a method for detecting a condition of multi-phase flow through a component having one or more media flowing therethrough includes providing within the component a first sensing cable aligned with a heating element and including at least one active optical fiber sensor at a first sensing location. The method includes providing within the component at least a second sensing cable including at least one optical fiber sensor at a second sensing location a predetermined distance from the first sensing location. The method includes propagating at least one heat pulse through the heating element along at least a portion of the first sensing cable to affect an exchange of thermal energy between the heating element and at least one medium exposed to the sensing cable and measuring, over time, a first temperature profile of the first sensing cable at the first sensing location corresponding to the heat pulse and a second temperature profile of the second sensing cable at the second sensing location corresponding to the heat pulse. The method includes determining a flow velocity of the one or more media flowing through the component by correlating the first temperature profile with the second temperature profile and detecting a condition of flow of the one or more media by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

In certain embodiments, the first sensing cable can include an active fiber optic sensor array having a plurality of active sensors, each active sensor having a location within the component, and the method can include measuring, over time, a temperature profile of the first sensing cable at each of the plurality of active sensors corresponding to the heat pulse. Detecting the condition of flow can include determining the phase of the at least one medium exposed to the sensing cable at each of the plurality of active sensors based on the corresponding temperature profile and the determined flow velocity. The plurality of active sensors can be arranged circumferentially along a perimeter of a wall of the component. Additionally, or alternatively, the plurality of active sensors are arranged in a grid pattern over a cross section of the component.

As embodied herein, detecting the condition of flow can include detecting an instantaneous phase fraction based upon the determined phase of the at least one medium at each of the plurality of active sensors and the location of each of the plurality of active sensors within the component. Additionally or alternatively, detecting the condition of flow can include detecting flow regime based upon the determined phase of the at least one medium at each of the plurality of active sensors over time and the location of each of the plurality of active sensors within the component.

In certain embodiment, the second sensing cable further includes a passive fiber optic sensor array having a plurality passive sensors and the method can include measuring, over time, a temperature profile of the second sensing cable each of the plurality of passive sensors corresponding to the heat pulse. The method can include determining a flow velocity of the one or more media flowing through the component at each of the plurality of active sensors by correlating the temperature profile of each of the active sensors with the temperature profile of at least a respective one of the passive sensors. Detecting the condition of flow can further include detecting a volumetric and mass flow rate of each phase of the instantaneous phase fraction of the one or more media based upon the determined flow velocity at each of the plurality of active sensors, the determined phase of the at least one medium at each of the plurality of active sensors, and the location of each of the plurality of active sensors within the component.

In accordance with another aspect of the disclosed subject matter a system for detecting a condition of multi-phase flow through a component having one or more media flowing therethrough includes a first sensing cable aligned with a heating element and including at least one active optical fiber sensor at a first sensing location within a component and at least a second sensing cable including at least one optical fiber sensor at a second sensing location, the second sensing location being at a predetermined distance from the first sensing location. The system includes an excitation source configured to propagate at least one heat pulse through the heating element along at least a portion of the first sensing cable to affect an exchange of thermal energy between the heating element and at least one medium exposed to the sensing cable. The system includes an optical signal interrogator coupled with the first sensing cable and the second sensing cable, to measure, over time, a first temperature profile of the first sensing cable at the first sensing location corresponding to the heat pulse, and a second temperature profile of the second sensing cable at the second sensing location corresponding to the heat pulse. The system includes a control unit, coupled to the optical signal interrogator, to determine a flow velocity of the one or more media flowing through the component by correlating the first temperature profile with the second temperature profile; and configured to detect a condition of flow of the one or more media by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

In certain embodiments, the first sensing cable can include an active fiber optic sensor array having a plurality of active sensors, each active sensor having a location within the component and the optical signal interrogator can be configured to measure, over time, a temperature profile of the first sensing cable at each of the plurality of active sensors corresponding to the heat pulse. The control unit can be configured to detect the condition of flow further by determining the phase of the at least one medium exposed to the sensing cable at each of the plurality of active sensors based on the corresponding temperature profile and the determined flow velocity. The plurality of active sensors can be arranged circumferentially along a perimeter of a wall of the component. Additionally or alternatively, the plurality of active sensors can be arranged in a grid pattern over a cross section of the component.

As embodied herein, the control unit can be configured to detect the condition of flow by detecting an instantaneous phase fraction based upon the determined phase of the at least one medium at each of the plurality of active sensors and the location of each of the plurality of active sensors within the component. Additionally or alternatively, the control unit can be configured to detect the condition of flow by detecting flow regime based upon the determined phase of the at least one medium at each of the plurality of active sensors over time and the location of each of the plurality of active sensors within the component.

In certain embodiments, the second sensing cable can include a passive fiber optic sensor array having a plurality passive sensors. The optical signal interrogator can be configured to measure, over time, a temperature profile of the second sensing cable each of the plurality of passive sensors corresponding to the heat pulse and the control unit can be configured to determine a flow velocity of the one or more media flowing through the component at each of the plurality of active sensors by correlating the temperature profile of at least a respective one of the active sensors with the temperature profile of each of the passive sensors. The control unit can be further configured to detect the condition of flow by detecting a volumetric and mass flow rate of each phase of the instantaneous phase fraction of the one or more media based upon the determined flow velocity at each of the plurality of active sensors, the determined phase of the at least one medium at each of the plurality of active sensors, and the location of each of the plurality of active sensors within the component.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and are intended to provide further explanation of the disclosed subject matter claimed.

The accompanying drawings, which are incorporated in and constitute part of this specification, are included to illustrate and provide a further understanding of the disclosed subject matter. Together with the description, the drawings serve to explain the principles of the disclosed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a schematic diagram of an exemplary sensing system in accordance with the disclosed subject matter.

FIG. **1**B is a cross sectional view of an exemplary sensing cable configuration in accordance with the disclosed subject matter.

FIG. **1**C is a cross sectional view of another exemplary sensing cable configuration in accordance with the disclosed subject matter.

FIG. **2** depicts a representative plot of current and heat pulses and corresponding temperature response in accordance with the disclosed subject matter.

FIG. **3** is a graph illustrating a direct temperature sensing technique for a plurality of sensor locations in accordance with the disclosed subject matter.

FIG. **4**A is a graph illustrating log-time regression sensing technique in accordance with the disclosed subject matter.

FIG. **4**B is a graph illustrating log-time regression sensing technique for a plurality of sensor locations in accordance with the disclosed subject matter.

FIG. **5**A is a graph illustrating thermal excitation energy concentration at harmonics and fundamental frequencies of heat pulses in connection with a frequency spectrum sensing technique.

FIG. **5**B is a graph illustrating the phase of a frequency-derivative spectrum in connection with frequency spectrum sensing techniques over a plurality of sensor locations in accordance with the disclosed subject matter.

FIG. **5**C is a graph illustrating the amplitude of a frequency-derivative spectrum in connection with frequency spectrum sensing techniques over a plurality of sensor locations in accordance with the disclosed subject matter.

FIG. **6** is a schematic representation of a system for determining flow distribution through a component in accordance with certain embodiments of the disclosed subject matter.

FIG. **7** is an image and graph illustrating an exemplary system and method for determining flow distribution through a component in accordance with the disclosed subject matter.

FIG. **8** is a schematic representation of a plurality of sensing cables arranged in grid patterns in accordance with certain embodiments of the disclosed subject matter.

FIG. **9** is a schematic representation of a system and method for detecting a condition of multi-phase flow in accordance with certain embodiments of the disclosed subject matter.

FIG. **10** is a schematic representation of a system and method for detecting a condition of multi-phase flow including a plurality of active sensors arranged in a grid pattern over a cross section of a component in accordance with the disclosed subject matter.

FIG. **11** is a schematic representation of a system and method for detecting a condition of multi-phase flow including a plurality of active sensors arranged circumferentially along a perimeter of a wall of a component in accordance with the disclosed subject matter.

DETAILED DESCRIPTION

As noted above and in accordance with one aspect of the disclosed subject matter, methods disclosed herein for detecting a condition of multi-phase flow in a component include providing within the component a first sensing cable aligned with a heating element and including at least one active optical fiber sensor at a first sensing location. The method includes providing within the component at least a second sensing cable including at least one optical fiber sensor at a second sensing location a predetermined distance from the first sensing location. The method includes propagating at least one heat pulse through the heating element along at least a portion of the first sensing cable to affect an exchange of thermal energy between the heating element and at least one medium exposed to the sensing cable and measuring, over time, a first temperature profile of the first sensing cable at the first sensing location corresponding to the heat pulse and a second temperature profile of the second sensing cable at the second sensing location corresponding to the heat pulse. The method includes determining a flow velocity of the one or more media flowing through the component by correlating the first temperature profile with the second temperature profile and detecting a condition of flow of the one or more media by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

Furthermore, systems for detecting a condition of multi-phase flow in a component are also provided. Such systems include a first sensing cable aligned with a heating element and including at least one active optical fiber sensor at a first sensing location within a component and at least a second sensing cable including at least one optical fiber sensor at a second sensing location, the second sensing location being at a predetermined distance from the first sensing location. The system includes an excitation source configured to propagate at least one heat pulse through the heating element along at least a portion of the first sensing cable to affect an exchange of thermal energy between the heating element and at least one medium exposed to the sensing cable. The system includes an optical signal interrogator coupled with the first sensing cable and the second sensing cable, to measure, over time, a first temperature profile of the first sensing cable at the first sensing location corresponding to the heat pulse, and a second temperature profile of the second sensing cable at the second sensing location corresponding to the heat pulse. The system includes a control unit, coupled to the optical signal interrogator, to determine a flow velocity of the one or more media flowing through the component by correlating the first temperature profile with the second temperature profile; and configured to detect a condition of flow of the one or more media by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

Reference will now be made in detail to the various exemplary embodiments of the disclosed subject matter, exemplary embodiments of which are illustrated in the accompanying drawings. The accompanying figures, where like reference numerals refer to identical or functionally similar elements, serve to further illustrate various embodiments and to explain various principles and advantages all in accordance with the disclosed subject matter. The accompanying figures, where like reference numerals refer to identical or functionally similar elements, serve to further illustrate various embodiments and to explain various principles and advantages all in accordance with the disclosed subject matter. For purpose of explanation and illustration, and not limitation, exemplary embodiments of the disclosed subject matter are shown in FIGS. **1-11**.

In accordance with the disclosed subject matter, characteristics of one or more materials can be measured with the use of an optical fiber sensor array having a plurality of sensor locations aligned with a heating/cooling element in a sensing cable. At least one heating/cooling pulse is propagated through the heating/cooling element along at least a portion of the sensing cable to affect an exchange of thermal energy between the heating/cooling element and one or more media exposed to the sensing cable. A temperature profile of the sensing cable (e.g., in the time domain and/or spatial domain) corresponding to the heating/cooling pulse at the plurality of sensor locations on the optical fiber sensor array can be measured to support a variety of techniques in accordance with the disclosed subject matter.

Generally, for purpose of illustration and not limitation, thermal properties, such as material density, thermal conductivity, heat capacity, or heat diffusion coefficient, of one or more materials can be measured by generating a heat disturbance and sensing a temperature response. In like fashion, dynamic physical properties, such as the flow of a material, can also be measured. As disclosed herein, techniques for measuring temperature can include obtaining temperature measurements in both the temporal and spatial domain. For example, distributed temperature sensing (DTS) systems can provide temperature measurements along the length of a sensing cable continuously or at regular intervals. The change in these temperature measurements can correspond to certain properties of a surrounding material or materials.

For purpose of illustration, and not limitation, an exemplary system for measuring the characteristics of a material in accordance with certain embodiments of the disclosed subject matter will be described. In general, with reference to FIG. **1**A, an exemplary sensing system in accordance with the disclosed subject matter can include a sensing cable **101** having disposed therein a heating/cooling device **103** and optical fiber sensor array having a plurality of sensors **102**. The sensing cable **101** can be operatively coupled with a control unit **106**. For example, the heating/cooling device **103** can be coupled with an excitation source **105**, which in turn can be coupled with the control unit **106**. Likewise, the optical fiber sensor array **102** can be coupled with a signal interrogator **104**, which can be coupled with the control unit **106**. Generally, uniform heat can be delivered (e.g., heat energy can be provided or absorbed) along the sensing cable **101** via the heating/cooling device **103** and the excitation source **105**. A temperature profile or its variation with time (e.g., variation rate) can be measured using the optical fiber sensor array **102** and signal interrogator **104**. The control unit **106** can be adapted to collect data, process data, and/or present data for visualization, for example via one or more displays (not shown).

The sensing cable **101** can be arranged in a variety of configurations. Two exemplary configurations are depicted in FIG. **1**B and FIG. **1**C, respectively. For example, FIG. **1**B depicts a cross section of a sensing cable **101** with the heating/cooling device **103** and the optical fiber sensor array **102** arranged in parallel with each other. The sensing cable **101** can include, for example, an outer casing (not shown) optionally filled with a filler material **110** to maintain the heating/cooling device **103** and optical fiber sensor array **102** in place. Additionally or alternatively, the filler can be extended about the heating/cooling device **103** and temperature sensor **102** with or without the outer casing. The filler can be, for example, a material with high thermal conductivity, such as magnesium oxide (MgO). The outer casing can be a rigid and/or durable material, for example a metal tube. To ensure measurement accuracy, e.g., under harsh conditions, such as fouling or corrosion, the sensing cable **101** casing can be treated with a suitable coating, as described in more detail below. Alternatively, and as depicted in cross section in FIG. **1**C, the heating/cooling device **103** and the temperature sensor array **102** can be generally coaxial with each other, wherein the heating/cooling device **103** is disposed concentrically around the temperature sensor array **102**.

As embodied herein, the sensing cable **101** can be mineral insulated for protection of a optical fiber sensor array **102** including one or more optical fibers. The optical fibers can be coated and placed into a protective tube structure for enhanced mechanical integrity and resistance to adversary effects of environmental factors, such as H_2, H_2S and moisture. The sensing cable **101** can further be protected using metal and mineral insulation material (e.g., MgO) for effective thermal conduction. The optical fibers can have a relatively small diameter, and thus can be placed into a protective tube with a relatively small diameter, allowing a faster thermal response and dynamic process monitoring. One of ordinary skill in the art will appreciate that the dimensions of the sensing cable **101** can be selected for a desired application. For example, if further protection from the local environment is desired, a sensing cable **101** with a larger diameter, and thus additional filler, can be selected.

Furthermore, a number of commercially available fibers for the temperature sensor **102** can be used, such as a Fiber Bragg Grating array, Raman scattering based sensor, Rayleigh scattering based sensor or Brillioun scattering based sensor. One of ordinary skill in the art will appreciate that each type of fiber sensor can have certain properties, such as response time, sensing resolution, immunity to hydrogen darkening, effective sensing cable length, and ability to sense temperature and/or strain, as illustrated for purpose of example and not limitation in Table 1. For example, a Fiber Bragg grating sensing system can include a relatively fast response time, high spatial resolution, and can be employed over a sensing cable length upwards of 100 km or longer in connection with the use of optical fiber amplifiers. Raman and Brillouin scattering sensing systems can have relatively low response times (e.g., on the order of several seconds), and spatial resolution on the order of centimeters. Rayleigh scattering sensing systems, when operated to sense temperature, can have a response time of several seconds with relatively high spatial resolution.

TABLE 1

Sensor types	Fastest response time	Typical point sensor size (m)	Immunity to H2 darkening	Longest sensor cable length
Fiber Bragg Grating (FBG)	<10 ms	0.01	high	<100 km or longer
Raman scattering sensor	>Several seconds	0.25~0.5	low	<100 km
Rayleigh scattering sensor (Temp)	>Several seconds	0.01	low	<70 m
Rayleigh scattering sensor (Acoustic)	<1 ms	0.5	low	<100 km
Brillouin scattering sensor	>Several seconds	0.1~50	low	<100 km

One of ordinary skill in the art will also appreciate that certain of the various types of sensing systems can be used to sense temperature and/or strain (e.g., to sense acoustics). For example, Fiber Bragg Grating sensing systems can be used to measure both temperature and strain, for purposes of sensing temperature and acoustics. Raman scattering sensing systems are typically used to sense temperature. Brillouin scattering sensing systems can be used to measure temperature and strain, and are typically used to sense temperature. Rayleigh scattering sensing systems can be used to measure temperature and strain, and can be used to sense either temperature or acoustics. One of ordinary skill in the art will appreciate that when Rayleigh scattering sensing systems are used to sense acoustics, response time can increase to lower than 1 ms and spatial resolution can increase to approximately 50 cm.

Referring again to FIG. **1**A, and as noted above, the control unit **106** can be coupled with the signal interrogator **104**. The signal interrogator **104** can be, for example, an optical signal interrogator. Various optical signal interrogators may be used, depending on the type of optical fiber sensing techniques to be employed. The controller **106** can be adapted to perform signal processing on real-time temperature data provided by the signal interrogator **104**. For example, the control unit **106** can be adapted to identify and record continuous or repeated temperature measurements at each of a plurality of sensor locations along the sensing cable **101**. Additionally, the control unit **106** can be adapted to process temperature measurements over time to identify a characteristic of the material surrounding the sensing cable at one or more sensor locations.

As disclosed herein, a variety of suitable methods can be employed for generating the heating/cooling pulse along the sensing cable **101**. As used herein, the term "pulse" includes a waveform of suitable shape, duration, periodicity, and/or phase for the intended purpose. For example, and not limitation, and as described further below, the pulse may have a greater duration for one intended use, such as the determination of deposits, and a shorter duration for another intended use, such as the determination of flow. As embodied herein, the heating/cooling device **103** can be an electrically actuated device. For example, the heating/cooling device **103** can include a resistive heating wire, and the excitation source **105** can be electrically coupled with the heating wire and adapted to provide a current therethrough.

Passing of a current through the resistive heating wire can provide thermal energy along the length of the sensing cable **101**, thereby generating a uniform heating/cooling effect along the sensing cable. Alternatively, the heating/cooling device **103** can include a thermoelectric device, and can be likewise coupled to the excitation source **105**. The thermoelectric device can use the Peltier effect to heat or cool a surrounding medium. That is, for example, the thermoelectric device can be a solid-state heat pump that transfers heat from one side of the device to the other. The thermoelectric device can be configured, for example, to provide heating to the optical fiber sensor for a certain polarity of electric potential and cooling for the opposite polarity. As disclosed herein, and for purpose of simplicity, the terms "heating/cooling device", and "heating/cooling pulse" will be referred to generally as a "heating device" or "heating element" and as a "heat pulse," respectively. Depending upon the context, such terms are therefore understood to provide heating, cooling, or both heating and cooling.

In certain embodiments of the disclosed subject matter, the excitation source **105** can be configured to deliver current in a predetermined manner. For example, the excitation source **105** can be configured to generate pulses having predetermined wave forms, such as square waves, sinusoidal waves, or saw tooth waves. The excitation source **105** can be configured to generate the pulses at a predetermined frequency. For example, and not limitation, and with reference to FIG. **2**, the excitation source **105** can be configured to generate an electric pulse of a rectangular wave form **210** through the heating/cooling element **103**. The electric pulse can create a heat pulse **220** in the heating/cooling element **103** with the same wave form. That is, for example, the heat flow through the heating/cooling element **103** can be given by I^2R/A, where I is the current, R is the resistance of the heating/cooling element **103**, and A is the surface area of a cross section of the heating/cooling element **103**. The heat pulse can result in a heat exchange between the sensing cable **101** and the surrounding media. The temperature at each sensor location can be recorded to generate a "temperature profile" **230** for each sensor location. For example, the temperature at each sensor location can be recorded with a sampling frequency of 50 Hz. The temperature profile **230** can correspond to characteristics of the medium surrounding the sensing cable **101** at each sensor location.

For purposes of illustration, and not limitation, the underlying principles of thermally activated ("TA") measurement techniques will be described generally. Prior to heating or cooling by the heating/cooling device **103**, temperature measurements of the surrounding medium can be taken with the optical fiber sensor array **102** of the sensing cable **101** and the temperature profile can be recorded as a reference. Due to the Joule effect, the heating device **103** can deliver a constant and uniform heat along the cable, heating up both cable and surrounding medium near the cable surface. For purposes of illustration, the temperature measured by the optical fiber can be described by the following equation:

$$\frac{\partial T}{\partial t} = \frac{1}{mc_p}(\dot{E}_{gen} - \dot{E}_{loss}), \tag{1}$$

where $\dot{E}_{gen}$ is the heat generation rate per unit length from the heating device, $\dot{E}_{loss}$ is the heat loss rate due to heat transfer from the sensing cable to the surrounding medium, and m and c_p represent the mass and heat capacitance of the sensing cable per unit length. The heat generation within the sensing cable due to the Joule effect can be given by:

$$\dot{E}_{gen} \propto Zi^2, \tag{2}$$

where Z is the impedance of the sensing cable per unit length and the rate of heat loss from the sensing cable to the surrounding media can be decomposed into heat diffusion and heat convection (e.g., $\dot{E}_{loss}$ can include both heat diffusion (conduction) in a stationary medium and or convective heat transfer in a flowing medium):

$$\dot{E}_{loss} = \dot{E}_{diffusion} + \dot{E}_{convection} \tag{3}$$

For a stationary medium, the heat loss term can be given as:

$$\dot{E}_{loss} \propto Ak\Delta T, \tag{4}$$

where A is effective heat transfer area of the sensing cable, k is effective heat conduction coefficient of the medium and ΔT is the effective temperature gradient across the sensing cable and the medium.

The heat capacitance of the cable per unit length can limit the frequency of the thermal response of the cable, and thus the cable can be designed with a heat capacitance suited to the desired data frequency. Because heat generation can be relatively constant and uniform, the rate of change in localized temperature can depend primarily on the heat transfer between the cable and the surrounding medium. If the localized heat transfer is high at a particular point on the sensing cable, then the rate of change of temperature at that point along the cable, measured by one temperature sensor in the optical fiber, can be small. Otherwise, the temperature changing rate will be large. When subject to a heterogeneous medium or a mixed medium consisting of layers of different fluids or the like, the spatial distribution of the temperature along the sensor array can be indicative of the interface between the different media.

For purpose of illustration, and not limitation, transient temperature analysis techniques to determine characteristics of a medium will now be described with the sensing cable modeled as an infinitely long thin cylinder placed in an infinite homogeneous medium. For purposes of this description, it is assumed that at time zero (t=0) an electrical current, i, and the heat generation rate per length of the cylinder is given by:

$$q = \pi r_0^2 z_0 i^2, \tag{5}$$

where r_0 is the radius of the cylinder, and z_0 is the resistance of the cylinder per unit of volume. A closed form solution for the temperature on the surface of the cylinder can be given as:

$$T(r_0, t) - T_\infty = \frac{q}{4\pi k}\int_{\frac{r_0^2}{4\alpha t}}^{\infty} \frac{e^{-u}}{u}du, \tag{6}$$

where k and α are the heat conductivity and diffusivity coefficients of the medium, and T_∞ is the initial temperature distribution along the sensing cable. The normalized temperature change and normalized time t can be defined as:

$$\Delta T^* = \frac{T(r_0, t) - T_\infty}{q/(4\pi k)} \tag{7}$$

and

$$t^* = \frac{4\alpha t}{r_0^2}. \tag{8}$$

Equation 6 can thus be given as:

$$\Delta T^* = \int_{1/t^*}^{\infty} \frac{e^{-u}}{u} du, \tag{9}$$

The incomplete gamma function can have following expansion form for small but non-zero value of z (0<z<2.5):

$$\Gamma(z) = \int_{z}^{\infty} \frac{e^{-u}}{u} du = -\gamma - \ln(z) - \sum_{n=1}^{\infty} \frac{(-z)^n}{n(n!)}. \tag{10}$$

The temperature response as given by equation 6 above can be further approximated as

$$\Delta T^* \approx -\gamma - \ln(1/t^*), \tag{11}$$

when

$$z = 1/t^* << 1. \tag{12}$$

In accordance with this illustrative and non-limiting model, comparison of the normalized temperature change as a function of normalized time (e.g., as given by equation 9 and equation 11, respectively) indicates that when the normalized time is greater than approximately 10, equation 11 is a good approximation of normalized temperature change. Moreover, equation 11 above indicates that temperature change can increase linearly with the log of time when the heating time is sufficiently large so as to satisfy the criteria in equation 12. Thus, the equation can be written as:

$$\Delta T(r_0, t) \approx a + b \ln(t), \tag{13}$$

where parameters a and b are function of thermal properties of the medium for given heating rate, and are given by:

$$a = \frac{q}{4\pi k}\left(-\gamma - \ln\left(\frac{r_0^2}{4\alpha}\right)\right) \tag{14}$$

and

$$b = \frac{q}{4\pi k}. \tag{15}$$

Thus, equation 13 can provide a theoretical basis for determining the thermal properties of a medium based on measurement of transient temperature. One of ordinary skill in the art will appreciate that continuous heating can consume more electrical energy and make measurements less sensitive to dynamic change of the thermal properties to be measured (e.g., when the medium mixture changes with time), and thus pulsed heating in accordance with the disclosed subject matter can provide benefits such as decreased electrical energy usage and for measurement of dynamic conditions of surrounding materials.

For purpose of illustration, and not limitation, an exemplary method of measuring the characteristics of the media surrounding the sensing cable using thermal analysis sensing techniques will be described. In general, an optimized waveform of electrical pulse (for example, a square wave) can be delivered along the length of the heating/cooling device **103**, and temperature can be monitored using a temperature sensor array **102**, e.g., optical fiber sensors. Owing to the uniformity of the heating/cooling effect along the sensing cable, temperature readings can vary depending on localized heat transfer process, which can be a function of the thermal properties (e.g., thermal conductivity, heat capacity) and physical conditions (static or flow) of the medium surrounding the sensing cable **101**. The control unit **106** can be adapted to determine the characteristics of the surrounding media simultaneously, using the temperature profile.

A single heating pulse (e.g., arising from an optimized waveform of electrical pulse) can create a temperature response which can be derived in accordance with the exemplary and non-limiting model described herein using superposition as follows:

$$T(r_0, t) - T_\infty = \frac{q}{4\pi k}\left(\int_{\frac{r_0^2}{4\alpha t}}^{\infty} \frac{e^{-u}}{u} du - \int_{\frac{r_0^2}{4\alpha(t-t_0)}}^{\infty} \frac{e^{-u}}{u} du\right). \tag{16}$$

The first term in the bracket of equation 16 can represent the heating from t to t_0, and the 2nd term the cooling after t_0. Data collected during heating and cooling are analyzed separately, as disclosed herein, to derivate estimates of thermal properties of the medium.

Based upon the above, the control unit **106** can be adapted to determine the characteristics of the surrounding media using a variety of suitable techniques. For example, the temperature profile at each sensor location can be used to determine the characteristics of the surrounding media directly. The temperature measurements during heating and/or cooling of the sensing cable, corresponding to the timing of the rectangular electrical pulse, can be used to generate a feature-temperature profile at each sensor location. For example, the feature-temperature profiles can be extracted from the temperature data at distinctive conditions: heating (e.g., the condition during which the heat pulse is passing over a sensor location), cooling (e.g., the condition during which the heat pulse has passed over the sensor location and heat is being exchanged between the sensing cable and the surrounding media) and peak temperature (e.g., approximately the maximum temperature recorded at the sensor location for each heat pulse).

For purpose of illustration, and not limitation, and with reference to FIG. **3**, the control unit **106** can be configured to determine temperature characteristics of surrounding media using the feature-temperature profile at each sensor location. FIG. **3** shows distribution of feature temperatures along a sensing cable exposed to different media at different sensor locations. Graph **330** depicts the measured temperature profiles for a plurality of sensor locations. In accordance with the disclosed subject matter, feature-temperatures **331***b*, **332***b*, and **333***b* can be extracted from the measured temperature profile depicted in graph **330**. For example, at each sensor location, feature-temperature **331***b* can correspond to a heating condition (e.g., while the heat pulse is passing over the sensor location), and can be extracted for each sensor location at a corresponding time **331***a*. Likewise, feature-temperature **332***b* can correspond to a peak temperature, and can be extracted for each sensor location at a corresponding time **332***a*. Similarly, feature temperature **333***b* can correspond to a cooling condition (e.g., after the heat pulse has passed over the sensor location and during which heat exchange between the cable and the surrounding media takes place) and can be extracted for each sensor location at a corresponding time **333***a*. Temperature **310** is the measured temperature at each sensor location during ambient conditions (e.g., no heat is applied).

As illustrated by FIG. **3**, the feature temperature at each sensor location can correspond to the temperature characteristics of the surrounding media. For example, as depicted in FIG. **3**, a 36 inch sensing cable arranged in a vertical configuration with a sensor disposed or located each unit inch along the cable can be exposed to a stack of air, oil, emulsion, and water. It should be noted that FIG. **3** depicts data from 24 sensor locations. Assuming each medium is stationary around the sensing cable, the rate of heat exchange, and thus the feature-temperature profiles **331***b*, **332***b*, and **333***b*, between the sensing cable and the surrounding media at each sensor location can correspond to the heat conduction of the surrounding media. That is, for example, heat transfer between the sensing cable and surrounding air can be lower than that between the sensing cable and water, as water has a higher heat conduction. Oil and emulsion layers can also be identified in this manner.

The determination of the characteristics of the media surrounding the sensing cable can be achieved by further configuring the control unit **106** to process the temperature profile. For example, in accordance with certain embodiments of the disclosed subject matter, the regression of the temperature over log of time can be performed over an interval of time corresponding to each heat pulse for each sensor location. The slope and intercept of the regression can be used to identify the material characteristics. For example, the regression can take the functional form of $T=b+m\ln(t)$, where T is the temperature measurement, ln(t) is the natural log of the time of the temperature measurement, b is the intercept of the regression, and m is the regression coefficient.

The interval over which the regression is taken can be, for example, during the heating condition described above (e.g., during which the heat pulse passes over the sensor location). Because heating can occur in a logarithmic manner, taking the regression as a function of the log of time and provide for results with lower error (e.g., a higher correlation coefficient). That is, for example, the temperature as a function of the log of time can be substantially linear over the heating period. Alternatively, the interval over which the regression is taken can be during the cooling condition described above. For purpose of illustration, and not limitation, for a square electrical pulse from 0 current to a constant non-zero value, the constant non-zero current value can correspond to the heating stage, and zero current can correspond to the cooling stage. The slope of the regression for the heating stage can be computed over a fraction of pulse duration when the current is non-zero, while slope of the regression for the cooling stage can be computed over a fraction of the time for which the current changes to zero value. Additionally or alternatively, the regression can take a number of suitable functional forms. For example, an nth order polynomial regression can be taken if the functional form of the temperature profile resembles an nth order polynomial.

For purpose of illustration, FIG. **4**A shows the regression results of one temperature measurement at a sensor location in each material of FIG. **3**. Line **420** corresponds to a plot of temperature at a sensor location in oil over the log of time. Likewise, lines **430**, **440** and **450** correspond to a plot of temperature at a sensor location in air, emulsion, and water, respectively, over the log of time. Regression can be performed over a regression interval **410**, which can correspond to the heating condition of the respective temperature sensor. The results of the regression can be plotted. For example, line **421** is a plot of the regression of line **420**. As illustrated by FIG. **4**A, the slope and intercept of each regression can correspond to a characteristic of the surrounding material, and such characteristics can be determined. That is, with reference to FIG. **4**A, each material having different thermal characteristics can have a different slope and intercept, and can thus be identified. As depicted in FIG. **4**A, The deviations in measurements resulting from the linear fitting line after the regression interval, as shown by line **420** and line **421**, can be due to boundary effects from the wall of the vessel. One of ordinary skill in the art will appreciate that the description of the underlying principles herein assumes the thermal energy delivered by the sensing cable diffuses out without any boundaries. However, in the presence of such boundaries, thermal energy will be contained in a finite space and eventually thermal equilibrium will be reached. Accordingly, the regression interval can be selected based on a desired application, including corresponding boundary conditions.

For purpose of illustration, FIG. **4**B shows the regression results for 24 temperature sensors of FIG. **3**, showing both slopes **450** and intercepts **470**. As illustrated by FIG. **4**A and FIG. **4**B, in certain circumstances these techniques can provide determination of material characteristics with reduced error, comparing results from FIG. **4**B with FIG. **3** to differentiate the emulsion layer and the oil layer. The interval over which the regression can be performed can be predetermined to reduce boundary effect errors (e.g., error **422** induced by boundary effects in the plot of line **420**). That is, for example, taking the regression over a small interval can omit certain features of a temperature profile that can correspond to a particular characteristic. Accordingly, the regression interval can be predetermined such that errors induced by boundary effects are reduced. For example, the regression interval can be predetermined by calibration and/or with reference to known parameters or operating conditions of the system, such as expected features of a temperature profile.

In accordance with another aspect of the disclosed subject matter, enhanced determination of the characteristics of media surrounding the sensing cable can be achieved with a control unit **106** configured to process the temperature profile in the frequency domain. A N-pulse train (i.e., application of a certain periodic form of current through the sensing cable to generate N cycles of heating and cooling) can be propagated through the heating/cooling element **103**. The period of a heating/cooling cycle, to, the number of heating cycles, N, and the current amplitude, I_0, can be selected. The heating/cooling pulses can be applied to the heating/cooling element **103** with the excitation source **105** to generate thermal excitation within the sensing cable **101**.

Temperature readings from the optical fiber sensor array **102** can be collected via the signal interrogator **104** at a selected sampling frequency. The sampling frequency can be, for example, at least twice the maximum signal frequency of interest. A temperature series, $T_i(1)$, $T_i(2)$, $T_i(3)$, . . . can be generated where i=1, 2, 3, . . . M, is the sensor index. In accordance with certain embodiments, synchronized sampling techniques can be employed to reduce the sample number, increase the signal to noise ratio, and improve Fourier transform accuracy. The time difference of the temperature readings $\Delta T=[T(k+1)-T(k)]/\Delta t$, can be calculated using the control unit **106** to generate time series of temperature derivative $\Delta T_i(1)$, $\Delta T_i(2)$, $\Delta T_i(3)$ . . . , where sensor index i=1, 2, 3 . . . M. In connection with the following description, the temperature difference, differenced temperature, or temperature derivatives are all referred to as the time series ΔT'. A transform (e.g., a Fast Fourier Transform [FFT], or Discrete Fourier Transform [DFT]) can be applied, using the control unit **106**, to generate a spectrum of time series of temperature difference for M sensors. For each sensor, the real and imaginary values of the spectrum at fundamental frequency of N-Pulse train can be selected $f_0=1/t_0$. The characteristics of the surrounding media can thus be determined as disclosed herein using M pairs of the values derived from the spectrum of the temperature difference as described above. Alternatively, the frequency differenced spectrum (i.e., obtained by applying the operation of taking the derivative of the spectrum of temperature difference with respect to the frequency) and the real and imaginary values of the differenced spectrum can be used. The characteristics of the surrounding media can thus be determined as disclosed herein using M pairs of the values derived from the differenced spectrum as described above.

That is, for example, the time derivative of the temperature data can be determined (i.e., resulting in the differenced temperature). The Fourier transform of the time-derivative temperature can then be determined, and the derivative of the complex spectrum with respect to the frequency can be calculated (i.e., resulting in the differenced spectrum). The amplitude and phase of the frequency-derivative spectrum (differenced spectrum) can then be calculated. The amplitude and phase of the frequency-derivative spectrum can correspond to the characteristics of the surrounding media at each sensor location. For purpose of illustration, FIG. **5**B shows the phase of the frequency-derivative spectrum of the temperature measurements over the sensor locations as illustrated in FIG. **3**. Likewise, FIG. **5**C shows the amplitude of the frequency-derivative spectrum of the temperature measurements over the sensor locations as illustrated in FIG. **3**. As illustrated by the figures, the techniques disclosed herein can provide for enhanced accuracy in the measurement and differentiation of the levels and interfaces between the air, oil, emulsion, and water layers.

As embodied herein, the sensing cable **101** can be calibrated, e.g., with the control unit **106**. Calibration can include calibrating the sensor array to ensure that each sensor at a different location along the sensing cable provides the same output when subject to the same material of a constant thermal property. For example, the sensing cable **101** can be submerged into a homogenous medium of known thermal property, and the temperature measurements and processing techniques disclosed herein can be applied. If there is a difference between sensor output, the difference can be used as compensation and can be applied during measurements. Additionally, calibration can include ensuring that the sensor output accurately estimates the particular characteristic of interest (e.g., thermal conductivity and/or diffusivity). For example, a number of materials with known thermal properties can be measured for a broad range of values and a database can be constructed including correlations between measurements and determined characteristics of the known materials. The database can then be used to interpolate a measured characteristic of an unknown material.

For purpose of illustration, and not limitation, the underlying theory of measurement techniques in accordance with this exemplary embodiment will be described. In connection with this description, for purpose of example, the waveform of the pulse train propagated through the heating device can be a square shape current, e.g., as illustrated in FIG. **2**. The current can be defined mathematically as:

$$i(t) = \sum_{n=1}^{N} \left\{ H(t-(n-1)t_0) - H\left(t - \left(n - \frac{1}{2}\right)t_0\right) \right\} I_0, \tag{17}$$

where t_0 is the period, I_0 is the amplitude of the current, and H denotes the Heaviside step function defined by:

$$H(x-x_0) = \begin{cases} 0 & x < x_0 \\ 1 & x \geq x_0 \end{cases}. \tag{18}$$

The heating rate can thus be given as:

$$q(t) = \sum_{n=1}^{N} \left\{ H(t-(n-1)t_0) - H\left(t - \left(n - \frac{1}{2}\right)t_0\right) \right\} q_0, \tag{19}$$

where q_0 is related to the current by equation 5.

Instead of analyzing the temperature in time domain, the temperature rate, i.e., the derivative of the temperature with respect to time, can be considered in the frequency domain. The derivative operation, a high-pass filtering, can remove the slow-varying trend of the temperature for easier analysis. The time derivative of the temperature and heating generation rate can be defined as follows:

$$\dot{T}(r, t) = \frac{dT}{dt} \tag{20}$$

and

$$\dot{q}(t) = \frac{dq}{dt}. \tag{21}$$

In frequency domain, the counterparts to the temperature and heating generation rate can be complex spectrum functions of $S(r, \omega)$ and $\Omega(\omega)$. For large distances away from the heating element, the thermal diffusion process can exhibit the behavior of an attenuated and dispersive wave. The complex spectrum of the change rate of the temperature on the sensing cable's surface can be given as:

$$S(r_0, \omega) = \frac{1}{2\pi k} \frac{\Omega(\omega)}{\kappa r_0} \frac{H_0^{(2)}(\kappa r_0)}{H_1^{(2)}(\kappa r_0)}. \tag{22}$$

The contribution of the heating component, Ω at a center frequency of ω, to the change rate of the temperature on the sensing cable's surface can thus be given as:

$$d\dot{T}(r_0, \omega, t) = S(r_0, \omega) e^{j\omega t} d\omega. \tag{23}$$

Integration of above over all frequencies can recover the temperature rate in time domain. Therefore, S can be used as indicator of the medium. For purpose of illustration, and not limitation, the excitation term, Ω will now be described in greater detail. From equations 19 and 21, the derivative of the heating generation can be given as:

$$\dot{q}(t) = \sum_{i=1}^{N} \left\{ \delta(t-(i-1)t_0) - \delta\left(t - \left(i - \frac{1}{2}\right)t_0\right) \right\} q_0 \tag{24}$$

in time domain, and:

$$\Omega(\omega) = q_0\left(e^{j\omega t_0} - e^{j\frac{\omega t_0}{2}}\right)\sum_{n=1}^{N} e^{j(n\omega t_0)} \tag{25}$$

in frequency domain. Because N is finite, Ω can contain all frequencies. The components at the harmonic frequencies can be given as:

$$\omega_k = k\omega_0 = k\frac{2\pi}{t_0}, \tag{26}$$

with index k.

Evaluation of equation 25 at the harmonic frequencies gives:

$$\Omega(\omega_k) = \begin{cases} 2Nq_0 & k = 1, 3, 5 \ldots \\ 0 & k = 0, 2 4 \ldots \end{cases}. \tag{27}$$

As such, Ω peaks at odd harmonics but zeros at even harmonics. At non-harmonic frequencies, Ω is complex in general. FIG. **5**A depicts an exemplary plot of Ω/q_0 verse ω/ω_0 for N=1, 2, or 3. Accordingly, the thermal excitation energy can be concentrated at odd harmonics of fundamental frequency of pulses and increase as N increases.

As embodied herein, one of the odd harmonic frequencies can be chosen to increase signal to noise ratio in analysis of temperature measurements. In this manner, any temperature variation introduced by non-electrical heating can introduce noise which could be difficult to handle in time domain but can be reduced in frequency domain via N-pulse train: the number of cycles, N, can be increased to boost the peak value at odd harmonics. Additionally or alternatively, synchronized sampling techniques or harmonic tracking can also be used to reduce the noise.

In accordance with certain embodiments, the spectrum S(ω), e.g., as given in equation 22, can be used to estimate the thermal property of a medium surrounding the sensing cable. A characteristic frequency can be given as:

$$\omega^* = \frac{\alpha}{r_0^2}. \tag{28}$$

The complex argument to the Hankel functions can thus become:

$$\kappa r_0 = \sqrt{-j\frac{\omega}{\alpha}}\, r_0 = \sqrt{\frac{\omega}{\omega^*}}\, e^{j\theta}, \tag{29}$$

Where θ=¾π for ω>0. At low frequencies where ω/ω* (amplitude of κr_0) is less than 1, the Hankel functions can be approximated as:

$$H_0^{(2)}(\kappa r_0) \approx 1 - \frac{(\kappa r_0)^2}{4} - j\frac{\pi}{2}\ln(\kappa r_0) \tag{30}$$

and:

$$H_1^{(2)}(\kappa r_0) \approx \frac{\kappa r_0}{2} - \frac{(\kappa r_0)^3}{16} + j\frac{2}{\pi}\frac{1}{\kappa r_0}. \tag{31}$$

The spectrum, S, can thus reduce to:

$$S(r_0, \omega) = \frac{\Omega}{2\pi k}\hat{X}\left(\frac{\omega}{\omega^*}\right), \tag{32}$$

where the normalized transfer function, and temperature change response to the thermal excitation Ω/2πk at frequency ω/ω* can be given as:

$$\hat{X}\left(\frac{\omega}{\omega^*}\right) = (R_s + jI_s) = Xe^{j\phi}, \tag{33}$$

$$R_s \approx \frac{\frac{1}{32}\left(\frac{\omega}{\omega^*}\right)^2 + \frac{1}{2\pi}\frac{\omega}{\omega^*} + \frac{1}{2\pi}\left(\frac{\omega}{\omega^*} - \frac{4}{\pi}\right)\ln\left(\frac{\omega}{\omega^*}\right)}{\frac{1}{4}\left(\frac{\omega}{\omega^*}\right)^2 - \frac{2}{\pi}\left(\frac{\omega}{\omega^*}\right) + \frac{4}{\pi^2}}, \text{ and} \tag{34}$$

$$I_s \approx \frac{\frac{5}{4}\left(\frac{\omega}{\omega^*} - \frac{4}{\pi}\right) - \frac{1}{16\pi}\left(\frac{\omega}{\omega^*}\right)^2\ln\left(\frac{\omega}{\omega^*}\right)}{\frac{1}{4}\left(\frac{\omega}{\omega^*}\right)^2 - \frac{2}{\pi}\left(\frac{\omega}{\omega^*}\right) + \frac{4}{\pi^2}}, \tag{35}$$

after neglecting terms of higher order.

As disclosed herein, and in accordance with certain embodiments of the disclosed subject matter, the amplitude and phase can decrease monotonically with frequency so that higher frequency corresponds with lower response of temperature to the heating. Accordingly, lower frequencies can obtain significant heating response and higher signals. Additionally, the imaginary part of the complex spectrum can be nearly linear with the frequency while the real part can exhibit linear behavior beyond certain frequency values. Therefore, the derivative of the transfer function spectrum with respect to frequency can lead to constants beyond certain values of ω/ω*. One of ordinary skill in the art will appreciate that, mathematically, the spectral derivative is equivalent to the Fourier transform of the temperature rate with respect to the log of time. Thus there is connection of the derivative spectrum with the linear relationship of the temperature change with log(t) in the time domain as shown in equation 13.

As embodied herein, systems and methods in accordance with the disclosed subject matter include determining the liquid/gas flow distribution of a fluid through a component with a sensing cable including an optical fiber sensor array aligned with a heating/cooling element. The method includes propagating at least one heating/cooling pulse through the heating/cooling element along at least a portion of the sensing cable to affect an exchange of thermal energy between the heating element and the fluid exposed to the sensing cable. The method includes measuring, over time, a temperature profile of the sensing cable corresponding to the heat pulse at each of a plurality of sensor locations on an optical fiber sensor array. The method includes determining a flow distribution of the fluid by determining one or more properties of the fluid exposed to the sensing cable at each of the plurality of sensor locations based on the temperature profile corresponding thereto.

For purpose of illustration and not limitation, reference is made to the exemplary embodiments of FIG. **1**. The method and system disclosed herein can be used to determine flow distribution in variety of components and vessels. For example, the component can be a particulate bed, a wash bed including packing material, an absorbent bed, a structured bed, a filter, or the like. In operation, it can be desirable to determine flow conditions through such components. For example, fixed bed reactors, such as hydrotreating reactors and hydrocracking reactors, can develop liquid/gas maldistribution and corresponding localized "hot spots," which can cause a runaway condition in exothermic reactions within the reactor. As another example, liquid/gas maldistribution can occur in components such as the wash beds of a vacuum pipe still ("VPS") distillation tower, which can cause problems such as unplanned capacity loss, increased operational costs, and increased energy usage. Determination of flow distribution of a fluid through such components can allow for mitigation strategies, such as increasing the flow rate of wash oil or otherwise varying operational parameters of the component. Accordingly, the techniques disclosed herein can be employed to determine the flow distribution of a fluid through a component in connection with a refining operation. However, it is recognized that the system and method herein can be applied to numerous other environments and vessels in which the determination of flow distribution is beneficial.

In accordance with this exemplary embodiment, the system for detecting a liquid/gas flow distribution vessel can include the components and features described herein with reference to FIG. **1**A-C. The sensing cable (e.g., sensing cable **101**) can further include an anti-fouling coating to resist fouling and/or coking deposition on the sensing cable. For example, the sensing cable can be coated with a suitable coating to resist coking, such as Teflon, or coatings formed from modified fluoropolymer and co-polymer reinforcements. These coatings can be engineered for high release (non-stick), non-wetting, thermal stability, dielectric strength and chemical resistance, where comparatively thin films are desired or otherwise beneficial.

Using the systems and techniques as disclosed, and suitable modifications as desired, a method of determining the flow distribution of a fluid through a component is provided and disclosed herein with reference to FIG. **1**A through FIG. **5**. For purpose of example, and with reference to FIG. **6**, the method of determining the flow distribution of a fluid through a component will be described in connection with certain exemplary embodiments, wherein the vessel is a fixed bed, such as in a fixed bed of a hydrotreating or hydrocracking reactor or a fixed structured wash oil bed of a VPS distillation tower. One of ordinary skill in the art will appreciate that the techniques disclosed herein can be applied in connection with a variety of suitable components, and the disclosed subject matter is not intended to be limited to the exemplary embodiments disclosed herein.

With reference to FIG. **6**, the method of flow through a vessel **810** can include positioning a sensing cable **101** within a wash bed **820** of a VPS distillation tower **810**. For example, the sensing cable **101** can be positioned across a surface of the wash bed **820** such that the sensing cable **101** is aligned perpendicular to an axis of the vessel **810**. In this manner, sensor locations along the sensing cable **101** can correspond to locations about a cross section of the vessel **810**. The sensing cable **101** likewise can be positioned and/or arranged in a variety of other suitable configurations as desired or needed. For example, the sensing cable **101** can be positioned parallel to an axis of the vessel **810** with the sensor locations along the sensing cable **101** generally correspond to locations along a vertical axis within the vessel **810**, such as along an inside wall of the vessel **810**. Moreover, as shown in FIG. **8**, the sensing cable **101** can be arranged in a grid pattern or array **911** and **912**, or any other suitable pattern, about a surface of the wash bed **820** or otherwise within the vessel **810**. One of ordinary skill in the art will also appreciate that more than one sensing cable can be employed. For example, as depicted in FIG. **8**, a second sensing cable **910**, which can also be positioned in a grid pattern, can be positioned on an opposite surface of the wash bed **820**.

As previously noted, the sensing cable **101** includes a heating/cooling element **103**, such as a heating wire, and an optical fiber sensor array **102**, as disclosed herein. The optical fiber includes a plurality of sensing locations along the length of the fiber, such that each sensing location corresponds to a position about the surface of the wash bed **820**. For example, and as previously noted, the optical fiber can include a plurality of sensors along its length and/or a single fiber sensor can be movable to define a plurality of sensor locations. The optical fiber sensor is coupled to an optical signal interrogator **104** to process an optical signal therein to obtain temperature measurements at each of the sensor locations. The optical signal interrogator **104** can further be coupled to a control unit **106** to process the temperature measurements.

As previously described herein, the heating wire is coupled to an excitation source **105** adapted to propagate electromagnetic waves (e.g., current **210**) through the heating wire, thereby creating corresponding heat pulses (e.g., heat pulse **220**). As the heat pulses propagate through the heating wire, heat is exchanged between the heating wire, the sensing cable, and the surrounding media at each sensor location. The temperature at each sensor location can be recorded, e.g., via the optical signal interrogator and control unit, to generate a temperature profile for each sensor location. For example, temperature can be measured as a function of time at each sensor location along the optical fiber. The temperature profile at each sensor location generally will correspond to the characteristics of the medium surrounding the sensing cable at that sensor location. In this manner, for purpose of illustration, sensor locations over which fluid in the vessel **810** is flowing can result in a temperature profiles distinguishable from sensor locations over which fluid is not flowing.

The temperature profile (i.e., the temperature as a function of time at a sensor location) can generally exhibit an increase in temperature coinciding with the exposure to the heat pulse at the corresponding sensor location. For purpose of illustration, and not limitation, and with reference to the laws of thermodynamics, the temperature will generally increase over the duration of the heat pulse at a rate corresponding to the characteristics of the surrounding media, and thereafter decrease as the heat from the heat pulse diffuses into the surrounding media at a rate corresponding to the characteristics of the surrounding media. Thus, the temperature profiles for each sensor location can correspond to the characteristics of the surrounding media, e.g., the rate of flow of the surrounding media. For example, and not limitation, at a sensing location over which the surrounding fluid has a substantial flow, the heat transfer from the heating wire into the surrounding media can be relatively high due to convective heat transfer arising from the flow, and thus a cold spot/region can be detected. By contrast, at a sensing location exposed to stationary media, the heat transfer from the heating wire into the surrounding media can be relatively low due to the lack of convective heat transfer, and thus a hot spot/region can be detected. That is, for purpose of illustration, and with reference to Equation 1 and Equation 3, heat loss at a particular sensor location can depend on the rate of flow of the fluid surrounding that sensor location due to convective heat transfer from the sensing cable into the surrounding fluid. Additionally, assuming a homogenous medium of constant temperature flowing within the component, the flow rate of the medium can be determined at each sensor location. Moreover, assuming a medium having a non-uniform temperature and substantially constant flow across the sensing cable, the temperature of the medium without heating pulse can be measured first, follow by measurement of the temperature of the medium with heating pulse. The difference between the temperature measurement without the heating pulse and the temperature measurements with the heating pulse can indicate the flow rate of the medium.

For purpose of illustration, and not limitation, reference will be made to an example of the method disclosed herein with reference to FIG. **7**. FIG. **7** includes an image **1210** of a sensing cable **1211** embedded between two layers of packing material. The sensing cable **1211** can include an optical fiber sensor array adjacent a heating wire. A water stream can be arranged to flow through a portion of the packing material (e.g., from the top layer, over the sensing cable **1211**, and through the bottom layer). As depicted in the image **1210** of FIG. **7**, the water stream is initially directed through the packing material at a location approximately corresponding to 10-20 cm along the sensing cable **1211**. As a heat pulse propagates through the heating wire, heat is exchanged between the heating wire, the sensing cable **1211**, the surrounding packing material, air, and the water stream flowing over the sensing cable **1211**. During heating, overall temperature readings at each sensor location increase, and the temperature profile reveals the location of the water stream. For example, FIG. **7** includes a plot **1220** of temperature (z-axis) versus sensor location in meters (x-axis) as a function of time (y-axis). Plot **1220** shows a trough of cooler temperature profiles corresponding to the water stream due to convective heat loss. The region **1223** of plot **1220** corresponds to the sensor locations along the sensing cable **1221** exposed to air and outside packing material, and illustrates a relatively higher temperature profile due to lack of convective heat loss. As depicted in FIG. **7**, at approximately 400 seconds, the water stream was moved back and forth about the sensing cable **1211**. As illustrated by plot **1220**, wherever the water flow passes over the sensing cable **1221**, the temperature profiles at corresponding sensor locations **1222** will be lower. The "Z" pattern represents a cold temperature region can is caused by the water stream moving back and forth.

As disclosed herein, the control unit thus can be adapted to determine the characteristics of the surrounding media at each sensor location using a variety of techniques, and thereby determine the flow distribution of a fluid through a component. For example, referring again to FIG. **6**, the control unit **106** can be adapted to determine, with reference to the known positions of the sensor locations and the corresponding temperature profiles, a relative rate of flow at each sensor location and thus determine the flow distribution of the media surrounding the sensing cable. In connection with the operation of a VPS distillation tower **810**, for example, vapor **1110** can flow upwards through one or more wash beds **820** such that different fractions (i.e., different petrochemicals in the vapor) can be separated. However, during operation, coking can occur on the wash bed, which can create uneven flow of vapor **1110** through the tower **810**. Accordingly, the methods disclosed herein can determine the flow distribution of the vapor **1110** and thus detect a maldistribution condition associated with coking. VGO wash oil **1120** can be introduced into the VPS distillation tower **810** to prevent the formation of coke deposits, for example upon detection of a coking condition. The methods disclosed herein can likewise determine the flow rate and distribution of the wash oil **1120**.

For purpose of illustration, and not limitation, the direct temperature measurement techniques described above can be used to determine the flow distribution of a fluid through a component. Particularly, a feature temperature profile (e.g., including three temperature measurements corresponding to a heating period, a peak temperature measurement, and a cooling period) can be extracted and processed to determine characteristics of the medium surrounding each sensor location. For example, and as depicted in FIG. **7**, the temperature profile of sensors exposed to a medium having a flow characteristic can have a relative low peak, heating, and cooling temperature relative to the temperature profile of sensors exposed to a stationary medium of the same kind.

Alternatively, and as described herein with reference to FIG. **4**B, a log-time regression technique can be used to determine certain characteristics of the medium surrounding each sensor location by further processing the temperature profile at each sensor location. That is, by performing the regression of the temperature over log of time over an interval of time corresponding to each heat pulse for each sensor location, the resulting slope and intercept of the regression can be used to identify characteristics of the medium. For example, the slope and intercept of sensor locations exposed to a medium having a flow characteristic can be distinguishable from the slope and intercept of sensor locations exposed to the same medium having a stationary characteristic.

In accordance with another exemplary embodiment of the disclosed subject matter, the frequency spectrum techniques disclosed herein with reference to FIG. **5**A-C can be employed to determine the flow distribution of a fluid through a component with increased measurement sensitivity, accuracy, and/or reliability. In this exemplary embodiment, and as described above, an N-pulse train can be propagated through the heating wire of the sensing cable **101** with pre-selected parameters, including heating cycle period, to, number of heating cycles, N, and current amplitude, I_0. The parameters can be selected according to the operating characteristics of the component such that the resulting temperature profile can be measured with a desired signal-to-noise ratio. For example, a longer heating cycle period or higher current amplitude can result in higher signal-to-noise ratio relative to a shorter heating cycle period or lower current amplitude. Likewise, an increase in the number of heating cycles can further increase the signal-to-noise ratio. One of ordinary skill in the art will appreciate that such parameters can be varied depending upon desired application. For example, if determination of flow distribution is desired at short time intervals, a shorter heating cycler period and a higher current amplitude can be employed. For purpose of example, and not limitation, in connection with a fixed bed reactor or VPS distillation tower having a diameter of approximately 20 to approximately 40 feet, approximately 4 to 5 layers of wash bed packing materials, and a total height of approximately 6 to approximately 10 feet. The heating cycle period for the sensing cable can be approximately 1 Hz or slower (i.e., the excitation source can be adapted to deliver a current pulse at 1 Hz or slower. The current amplitude can be several milli-amperes to several amperes. One of ordinary skill in the art will appreciate that, in accordance with the disclosed subject matter, suitable frequency and current amplitude can be determined for a particular application by routine testing in accordance with known methods.

The optical signal interrogator **104** can be adapted to measure temperatures from the optical fiber at a pre-selected sampling frequency. In accordance with certain embodiments, the sampling frequency can be at least twice the expected frequency of the temperature profile and/or heat pulse. For example, and not limitation, in connection with a fixed bed reactor or VPS distillation tower, the sampling frequency can be 10 Hz. The derivative with respect to time of the temperature measurements for each sensor location can then be generated. For example, the measured temperatures a sensor location at each sampling interval can be given as a temperature series. The difference between each temperature in the series can then be calculated to generate a temperature derivative series. A transform (e.g., a FFT or DFT) can be applied to convert the temperature derivative series into the frequency domain, and thus generate a spectrum of time series of temperature differences for each sensor location. The derivative of the spectrum, with respect to the frequency, can be generated. That amplitude and phase of the frequency-derivative spectrum (e.g., the real and imaginary parts of the complex frequency-derivative spectrum) can then be determined. For example, using the heating cycle period, to, the real and imaginary values of the spectrum at the fundamental frequency of the N-pulse train can be selected at $f_0=1/t_0$.

The amplitude and phase of the frequency-derivative spectrum at each sensor location thus can correspond to the characteristics of the medium surrounding the sensing cable **101** at a particular sensor location. For example, the amplitude and phase can decrease monotonically with frequency so that higher frequency corresponds with lower response to a change in temperature from the heating element. Accordingly, lower frequencies can obtain significant heating response and higher signals. Additionally, the imaginary part of the complex spectrum can be nearly linear with the frequency while the real part can exhibit linear behavior beyond certain frequency values. Therefore, the derivative of the transfer function spectrum with respect to frequency can correspond to the linear relationship of the temperature change with log(t) in the time domain. In this manner, the amplitude and phase of sensor locations exposed to a flowing medium can be distinguishable from the amplitude and phase of sensor locations exposed to non-flowing medium of the same kind, or a higher-velocity flowing medium from a lower-velocity flowing medium.

The sensing cable **101** can be calibrated, e.g., with the control unit. Calibration can include, for example, calibrating the sensor array to determine the amplitude and phase of the frequency-derivative spectrum of certain known media. For example, a number of materials with known thermal properties can be measured for a broad range of values and for a broad range of flow rates, and a database can be constructed including correlations between the generated amplitude and phase and characteristics, such as flow rate, of the known materials. The database can then be used as to determine the flow rate of the surrounding medium at a particular sensor location in the vessel.

The control unit **106**, with reference to the known locations of each sensor and the corresponding amplitude and phase of the frequency-derivative spectrum, can determine the flow distribution of a fluid through the component. To determine the flow distribution, the control unit can be configured to store the known position of each sensor location in one or more memories. For example, for a 36 inch long sensing cable, having 36 sensor locations each spaced apart by a unit inch, positioned about the surface of a 36 inch wash bed **820**, the control unit can store the distance of each sensor location from the wall of the component **810** (i.e., for sensor location i={1, 2, . . . , 36}, the control unit can store a corresponding distance measurement D_i={1 in, 2 in, . . . , 36 in}). For each sensor location, i, the control unit can determine the amplitude and phase of the frequency derivative spectrum as disclosed herein. With reference to, for example, a database storing the amplitude and phase of the frequency derivative spectrum for known flow rates of the known media, the control unit can thus determine the relative flow rate at each sensor location and thus the flow distribution using the determined amplitude and phase at each sensor location.

Additionally or alternatively, and as embodied herein, the control unit can process the determined amplitude or phase of the frequency derivative spectrum of adjacent sensor locations to determine the flow distribution. That is, for example, assuming the vessel contains media with otherwise constant characteristics, a change in the amplitude across two sensor locations can correspond to a different flow rate across the two sensor location. Likewise, a change in the phase can correspond to a different flow rate of the same media. In certain embodiments, the control unit can process both the amplitude and phase of adjacent sensors to enhance determination of flow distribution. For example, a change in both the amplitude and phase can correspond a different flow rate across the two sensors. Moreover, in certain embodiments, the control unit can monitor the amplitude and phase of each sensor location over time (e.g., throughout the operation of a VPS distillation tower) and determine whether the temperature profile of one or more sensor locations changes with time. For example, the control unit can be configured to monitor the temperature profile of one or more sensor locations over time, identify a change in said temperature profile and, with reference, e.g., to a database of known characteristics corresponding to flow rate, determine the flow distribution.

In another exemplary embodiment, multiple layers of sensors can be deployed between different layers of packing materials, for example as depicted in FIG. **8**. Measurement from each layer of sensor can reveal localized conditions, such as the flow rate at each sensor location. In this manner, entrainment of resid can be inferred by comparison of measurement results across sensor layers.

The techniques disclosed herein can provide for continuous determination of flow distribution through a component. No moving mechanical parts need be included inside the sensing cable. Because material thermal properties can be measured for determination of flow distribution, the measurement results can be independent of electrical conductivity, salinity, and crude oil constituents, such as sulfur, iron sulfide/oxide. Moreover, relative temperature changes before and after heating/cooling can be used to infer material thermal properties for determination of flow distribution, and temperature baseline can be taken each time before heating/cooling is applied. Accordingly, the methods disclosed herein need not require long term stability for temperature sensors.

Moreover, the system disclosed herein can operate at temperatures ranging from cryogenic temperatures up to over 1000° C. The size of the sensing cable can be relatively small (e.g., compared to conventional thermocouples) and can be cost effective for large area coverage with a large amount of sensors. Utilizing cost-effective optical fiber temperature sensors, the system disclosed herein can incorporate a large number of sensors, and can offer a high spatial resolution, e.g., less than 1 mm, over a long measurement range, e.g., several meters to kilometers. The diameter of the compact sensing cable can small, e.g., less than 2 mm. The small diameter of the sensing cable can allow for measurement in a tight space with reduced intrusiveness. Furthermore, the heating/cooling element can be turned off, and the sensing cable can be converted to a temperature sensor, which can provide absolute temperature measurements inside the vessel, such as measurements of the wash bed packing materials. Such absolute temperature measurements can be used to infer liquid/vapor distributions, for example, inside packing materials, where temperature differences between liquid and vapor

Additionally and/or alternatively to the systems and methods for determining fluid flow distributions, as described above, the disclosed subject matter further includes systems and methods for detecting a condition of multi-phase flow through a component having one or more media flowing therethrough. The method includes providing within the component a first sensing cable aligned with a heating element and including at least one active optical fiber sensor at a first sensing location. The method includes providing within the component at least a second sensing cable including at least one optical fiber sensor at a second sensing location a predetermined distance from the first sensing location. The method includes propagating at least one heat pulse through the heating element along at least a portion of the first sensing cable to affect an exchange of thermal energy between the heating element and at least one medium exposed to the sensing cable and measuring, over time, a first temperature profile of the first sensing cable at the first sensing location corresponding to the heat pulse and a second temperature profile of the second sensing cable at the second sensing location corresponding to the heat pulse. The method includes determining a flow velocity of the one or more media flowing through the component by correlating the first temperature profile with the second temperature profile and detecting a condition of flow of the one or more media by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

For purpose of illustration and not limitation, reference is made to the exemplary embodiments of FIG. **9**. The method and system disclosed herein can be used to detect a variety of multi-phase flow conditions, including for example flow regime (such as full flow, slug flow, bubble flow, annular flow, and the like), flow phase fraction cross section, volumetric and mass flow rate of each phase, and/or instantaneous and statistical average over a given time. Furthermore, the method and system disclosed herein can be used to detect a condition of multi-phase flow in a variety of components. For example, the system and method disclosed herein can be used to meter production from a gas or oil well, to troubleshoot an irregular flow in a pipe in a refinery or chemical plant, and/or to identify a leak in a pipeline. For purpose of illustration, and not limitation, the techniques disclosed herein will be described with reference to detection of a condition of multi-phase flow in a pipe. However, it is recognized that the system and method herein can be applied to numerous other environments and components in which the detection of a condition of multi-phase flow is beneficial or desired.

With reference to FIG. **9**, the method for detecting a condition of multi-phase flow through a component (e.g., pipe **910**) having one or more media (e.g., water **911** and gas **912**) flowing therethrough can include providing within the pipe **910** a first sensing cable **101** aligned with a heating element and including at least one active optical fiber sensor at a first sensing location S**1**. The first sensing cable can be, for example, the sensing cable **101** described with reference to FIG. **1**A-C including heating element **103** and optical fiber **102**. At least a second sensing cable **902** including at least one optical fiber sensor at a second sensing location a can be provided within the component a predetermined distance from the first sensing location S**1**. For example, the second sensing location can be provided at location S**2** with reference to FIG. **9**. FIG. **9** depicts, for purpose of illustration and not limitation, a cross sectional view **920** of pipe **910** at the first sensing location S1 and a cross sectional view **930** of pipe **910** at the second sensing location S**2**. The first sensing location S1 and the second sensing location S**2** can be separated by a distance d within the pipe **910** along a longitudinal axis of pipe **910**. The first sensing location S**1** can be positioned upstream from the second sensing location S**2**.

At least one heat pulse can be propagated through the heating element along at least a portion of the first sensing cable **101** to affect an exchange of thermal energy between the heating element and at least one medium (e.g., **911** or **912**) exposed to the sensing cable. A first temperature profile **940** of the first sensing cable **101** at the first sensing location S**1** corresponding to the heat pulse can be measured over time. A second temperature profile **950** of the second sensing cable **902** at the second sensing location S**2** corresponding to the heat pulse can also be measured over time. The first temperature profile **940** can be correlated with the second temperature profile **950** to determine a flow velocity of the one or more media flowing through pipe **910**. For example, and not limitation, the known distance d separating the first and second sensor locations S**1** and S**2** can be used to determine a time delay τ representative of the time taken for the thermal energy generated by the heat pulse at the first sensor location S**1** to reach the downstream second sensor location S**1**, and thus the velocity of the media flowing through pipe **910**.

In accordance with certain embodiments, the time delay, τ, measures the time of transportation of the heat pulse from the first sensor location, S**1**, to the second sensor location, S**2**, and can be determined by a number of methods, for example by detecting the arrival time of a leading edge or peak of the pulse, and/or by cross correlation analysis. The cross correlation of the temperature profile $T_1(t)$ and $T_2(t)$ measured at sensor locations S**1** and S**2** respectively over a time period of T can be given as:

$$R_{21}(\tau^*) = \frac{1}{\tau}\int_0^{\tau} T_1(t)T_2(t+\tau^*)dt. \tag{36}$$

The transportation time of the pulse, τ, is equal to the value of τ* that maximize R_{21}. The instantaneous velocity of one or more media (e.g., **911** and **912**) flowing through pipe **910** at location S_1 given by its Cartesian coordinates (x_1, y_1 and z_1) in the direction from S1 to S2 can then be determined by

$$V(x_1, y_1, z_1, t) = \frac{d}{v}. \tag{37}$$

A condition of flow of the one or more media can be detected by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location S**1** based on the first temperature profile **940** and the determined flow velocity. That is, the phase of the medium at the first sensor location **S1** can be determined by decoupling the heat transferring effects due to the flow velocity and due to the fluid phase's thermal properties. As in equation 3, the overall heat exchange rate between the sensing cable and surrounding medium is due to both heat conduction and convection, depending on both flow velocity and thermal properties of the medium. The overall heat exchange rate of sensing cable to the surrounding medium can be expressed as follows:

$$\dot{E}_{loss} = A_c h \Delta T, \tag{38}$$

where h is effective overall heat transfer coefficient, A_c is the effective heat transfer area of the sensing cable, and ΔT is the effective temperature gradient across the sensing cable and the medium in the direction of flow. The heat transfer due to flow can depend on a dimensionless number, which can be referred to in the art as the Nusselt number, which can be given as

$$N_u = \frac{hL}{k}, \tag{39}$$

where k is the heat conductivity of the medium and L is the characteristics length (e.g., the diameter of the sensing cable, D). For a prescribed geometry (e.g., sensing cable, pipe, and flow direction), the Nusselt number can be represented as a function of Reynolds and Prandtl numbers. The Reynolds number, which can correspond to flow, can be given by

$$R_e = \frac{VD}{\mu/\rho}, \tag{40}$$

and Prandtl number, which can correspond to medium properties, can be given by

$$P_T = \frac{c_p \mu}{k}, \tag{41}$$

where μ is the viscosity, p is the density of the medium, C_p is the specific heat capacity of the medium, and V is the velocity. The dependence of N_u as a function of R_e and P_r can vary for different ranges of R_e and P_r values, and can be derived empirically in accordance with techniques known the art. For purpose of illustration, and not limitation, the Nusselt number, over a practical range of flow velocity and mediums of interest, can be expressed in the following form:

$$N_u = A + BR_e^m \tag{42}$$

where the coefficients A and B depend on the value P_r or medium properties only, and m is a constant. The overall heat transfer coefficient can then be expressed as:

$$h(\text{medium properties, velocity}) = \frac{N_u k}{L} = a(\text{medium}) + b(\text{medium})V^m. \tag{43}$$

Once the velocity, V, at the first sensor location is determined from equation 37, the phase of the medium can be estimated from equation 43 above.

For purpose of illustration, and not limitation, an example of a multiphase flow system of gas, water, and oil, which can be common in petroleum industries such as flow in a producing well, is provided. Assuming that the instantaneous phase of the media at location **S1** at time t is one of three phases, gas, water and oil, the instantaneous heat transfer coefficient at the sensor location **S1** can be expressed as

$$h_k(S1,t) = a_k + b_k V^m(S1,t) \tag{44}$$

where k can be assigned as 1 (gas), 2 (water), and 3 (oil). The calibration of h as a function of flow velocity for gas, water and oil can be made to determine the value of the coefficient a, b and m. Since the value of P_r are very different among gas, water and oil, it is expected that the values of a and b for each phase are distinct, and leads to different curves of heat transfer coefficient, h, verse flow velocity, V for different phase. Since any measurement method (e.g., characteristic temperature such as heating, cooling or peak temperature, log regression, or frequency spectrum magnitude or phase) discussed previously measures the heat transfer coefficient h, the calibration curves can be developed for specific measurement method with which classification rules are developed to classify the phase at **S1** based on the value of measurements.

In connection with this non-limiting example, and to demonstrate phase determination, the instantaneous phase of the media at location **S1** and at time t can be assumed to be one of three phases: gas, water and oil, and described by a binary phase indicator defined as follows:

$$P_k(S1, t) = \begin{cases} 1 & \text{if } S1 = \text{phase } k \\ 0 & \text{if } S1 \neq \text{phase } k \end{cases} \tag{45}$$

With the flow velocity determined at **S1**, the phase at **S1** can be classified into one of three phases based on comparison of the feature of temperature measurement at **S1** and calibration data. The value of the phase indicator can be assigned, and the phase flow rate can be calculated as follows:

$$\Delta Q_k(S1, t) = P_k(S1, t)V(S1, t)\Delta A_1, \tag{46}$$

for k=1, 2, or 3 where ΔA_1 is a very small area around the location **S1** within which the phase can be assumed to be the same.

In addition to the instantaneous flow at **S1**, the average flow rate can also be determined and can be used for applications such as flow metering. The volumetric flow rate of each phase at **S1** averaged over a time period from t to t+T can be given by

$$\Delta \overline{Q}_k(S1, t, T) = \frac{\Delta A_1}{T} \int_{\tau}^{\tau+T} P_k(S1, \theta)V(S1, \theta)d\theta \tag{47}$$

Time averaged volumetric flow rate at **S1** can thus be given by

$$\Delta\overline{Q}(S1,t,T)=\sum_{k=1}^{3}\Delta\overline{Q}_k(S1,t,T)=\frac{\Delta A_1}{T}\int_{\tau}^{t+T}V(S1,\theta)d\theta. \tag{48}$$

If the phase density, ρ_k, is known, the time-averaged local mass flow rate at S1 can be given by

$$\Delta\overline{M}(S1,t,T)\sum_{k=1}^{3}\rho_k\Delta\overline{Q}_k \tag{49}$$

The local phase fraction at S1 within the time period of T can be given by

$$\Delta\overline{\phi}_k(S1,t,T)=\frac{\Delta\overline{Q}_k}{\Delta\overline{Q}} \tag{50}$$

In addition to the instantaneous flow at **S1**, the average flow rate can also be determined and can be used for applications such as flow metering. The volumetric flow rate of each phase at **S1** averaged over a time period from t to t+T can be given by

Time averaged volumetric flow rate at **S1** can thus be given by

If the phase density, ρ_k, is known, the time-averaged local mass flow rate at **S1** can be given by

The local phase fraction at **S1** within the time period of T can be given by

This non-limiting example illustrates the basic principal of determining local flow condition of multiphase flow when a pair of sensors is used. One of skill in the art will appreciate, however, that flow conditions of multiphase flow can also be determined with multiple pairs of sensors.

For purpose of illustration, and not limitation, additional exemplary embodiments will be described with reference to FIG. **10** and FIG. **11**. In accordance with these exemplary embodiments, the first sensing cable can include an active fiber optic sensor array having a plurality of active sensors. Additionally or alternatively, the second sensing cable can also include a fiber optic sensor array having a plurality of sensors. A temperature profile of the first sensing cable at each of the plurality of active sensors corresponding to the heat pulse can thus be measured over time. Detecting the condition of flow can include determining the phase of the at least one medium exposed to the sensing cable at each of the plurality of active sensors based on the corresponding temperature profile and the determined flow velocity.

With reference to FIG. **10**, for example, the plurality of active sensors (e.g., **1001***a*, **1001***b*) can be arranged in a grid pattern over a cross section of the component **910**. Additionally or alternatively, the plurality of active sensors (e.g., **1101***a*, **1101***b*) can be arranged circumferentially along a perimeter of a wall of the component **910**.

As embodied herein, detecting the condition of flow can include detecting an instantaneous phase fraction based upon the determined phase of the at least one medium at each of the plurality of active sensors and the location of each of the plurality of active sensors within the component. For example, and not limitation, consider the multiphase flow in a circular pipe and N of optical fiber sensor pairs in a grid pattern as shown in FIG. **10**. Each pair of sensors consists of an active fiber optical sensor in the first sensing cable at sensor location $\mathbf{S1}_i$ and a temperature fiber optical sensor at sensor location, $\mathbf{S2}_i$. The two sensors can be separated by a known distance of d and their axis can be parallel to the flow. The pipe cross section can be divided in to N subsections with each subsection associated with a sensor. The local flow velocity, V, phase indicator, P_k, and local phase volumetric flow rate, ΔQ_k, at sensor location $\mathbf{S1}_i$ and at time t, can be measured and estimated with the method described previously. The instantaneous volumetric flow rate of each phase in the pipe can then be given by

$$Q_k(t)=\sum_{i=1}^{N}\Delta Q_k(S1_t,t) \tag{51}$$

and instantaneous total volumetric flow can be given by

$$Q(t)=\sum_{k=1}^{3}Q_k(t). \tag{52}$$

Similarly the instantaneous mass flow rates can be given by

$$M_k(t)=\rho_k Q_k(t) \tag{53}$$

and

$$M(t)=\sum_{k=1}^{3}M_k(t). \tag{54}$$

In addition, the instantaneous phase fraction at time t at active sensor i can be given by

$$\phi_k(t)=\frac{Q_k}{Q}. \tag{55}$$

One of skill in the art will further appreciate that time-averaged values of above parameters can likewise be derived.

Moreover, as embodied herein, detecting the condition of flow can include detecting flow regime based upon the determined phase of the at least one medium at each of the plurality of active sensors over time and the location of each of the plurality of active sensors within the component. For example, the phase fraction can be measured, over time, and recorded. A slug flow regime can be determined by comparing the phase fraction, over time, to identify an increase in gas phase relative to liquid phase.

As disclosed herein, the control unit can be adapted to determine the characteristics of the surrounding media at each sensor location using a variety of techniques, and thereby determine the a characteristic of multi-phase flow of the one or more media flowing through the component. For purpose of illustration, and not limitation, the direct temperature measurement techniques described above can be used to determine the a condition of multi-phase flow. Particularly, a feature temperature profile (e.g., including three temperature measurements corresponding to a heating period, a peak temperature measurement, and a cooling period) can be extracted and processed to determine characteristics of the medium surrounding each sensor location.

Alternatively, and as described herein with reference to FIG. **4**B, a log-time regression technique can be used to determine certain characteristics of the medium surrounding each sensor location by further processing the temperature profile at each sensor location. That is, by performing the regression of the temperature over log of time over an interval of time corresponding to each heat pulse for each sensor location, the resulting slope and intercept of the regression can be used to identify characteristics of the medium. For example, the slope and intercept of sensor locations exposed to a medium having a flow characteristic can be distinguishable from the slope and intercept of sensor locations exposed to the same medium having a stationary characteristic.

In accordance with another exemplary embodiment of the disclosed subject matter, the frequency spectrum techniques disclosed herein with reference to FIG. **5**A-C can be employed to determine the a condition of multi-phase flow through a component with increased measurement sensitivity, accuracy, and/or reliability. In this exemplary embodiment, and as described above, an N-pulse train can be propagated through the heating wire of the sensing cable **101** with pre-selected parameters, including heating cycle period, to, number of heating cycles, N, and current amplitude, I_0. The parameters can be selected according to the operating characteristics of the component such that the resulting temperature profile can be measured with a desired signal-to-noise ratio. For example, a longer heating cycle period or higher current amplitude can result in higher signal-to-noise ratio relative to a shorter heating cycle period or lower current amplitude. Likewise, an increase in the number of heating cycles can further increase the signal-to-noise ratio. One of ordinary skill in the art will appreciate that such parameters can be varied depending upon desired application. For example, if determination of multi-phase flow condition is desired at short time intervals, a shorter heating cycler period and a higher current amplitude can be employed. For purpose of example, and not limitation the heating cycle period can be approximately several milliseconds to several seconds (i.e., the excitation source can be adapted to deliver a current pulse at approximately 0.01 Hz to 100 Hz). The current amplitude can be approximately 1 mA to approximately 1 A. One of ordinary skill in the art will appreciate that, in accordance with the disclosed subject matter, suitable frequency and current amplitude can be determined for a particular application by routine testing in accordance with known methods.

ADDITIONAL EMBODIMENTS

Additionally or alternately, the invention can include one or more of the following embodiments.

Embodiment 1

a method for detecting a condition of multi-phase flow through a component having one or more media flowing therethrough, comprising: providing within a component a first sensing cable aligned with a heating element and including at least one active optical fiber sensor at a first sensing location; providing within the component at least a second sensing cable including at least one optical fiber sensor at a second sensing location, the second sensing location being at a predetermined distance from the first sensing location; propagating at least one heat pulse through the heating element along at least a portion of the first sensing cable to affect an exchange of thermal energy between the heating element and at least one medium exposed to the sensing cable; measuring, over time, a first temperature profile of the first sensing cable at the first sensing location corresponding to the heat pulse; measuring, over time, a second temperature profile of the second sensing cable at the second sensing location corresponding to the heat pulse; determining a flow velocity of the one or more media flowing through the component by correlating the first temperature profile with the second temperature profile; and detecting a condition of flow of the one or more media by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

Embodiment 2

the method of any of the previous embodiments, wherein measuring the temperature profile corresponding to the heat pulse at the first sensing location includes measuring at least a heating temperature measurement during propagation of the heat pulse over the sensor location, a peak temperature measurement, and a cooling temperature measurement after propagation of the heat pulse over the sensor.

Embodiment 3

the method of any of the previous embodiments, wherein measuring the temperature profile corresponding to the heat pulse at the first sensing location includes measuring a plurality of temperatures over a period of time upon arrival of the heat pulse at the sensor location.

Embodiment 4

the method of embodiment 3, wherein determining the phase of the medium exposed to the sensing cable at the first sensing location includes performing a regression of the plurality of temperatures over a logarithm of corresponding measurement times for a predetermined time window in the period of time to generate a slope and an intercept of the regression, wherein the slope and the intercept relate to the phase of the medium exposed to the sensing cable at the first sensing location.

Embodiment 5

the method of embodiment 3 or 4, wherein determining the phase of the medium exposed to the sensing cable at the first sensing location includes: generating a time derivative by calculating a derivative of the plurality of temperature measurements with respect to time; applying a transform to the time derivative to generate a complex spectrum; and determining an amplitude and a phase of the complex spectrum, wherein the amplitude and the phase of the complex spectrum relate to the phase of the medium exposed to the sensing cable at first sensing location.

Embodiment 6

the method of embodiment 5, wherein determining the phase of the media exposed to the sensing cable at the first sensing location further includes: generating a frequency derivative spectrum by calculating the derivative of the complex spectrum with respect to frequency; and determining an amplitude and a phase of the frequency derivative spectrum, wherein the amplitude and the phase of the frequency derivative spectrum relate to the phase of the medium exposed to the sensing cable at the first sensing location.

Embodiment 7

the method of any of the previous embodiments, wherein the first sensing cable includes an active fiber optic sensor array having a plurality of active sensors, each active sensor having a location within the component, the method further comprising: measuring, over time, a temperature profile of the first sensing cable at each of the plurality of active sensors corresponding to the heat pulse; and wherein detecting the condition of flow further comprises determining the phase of the at least one medium exposed to the sensing cable at each of the plurality of active sensors based on the corresponding temperature profile and the determined flow velocity.

Embodiment 8

the method of embodiment 7, wherein the plurality of active sensors are arranged circumferentially along a perimeter of a wall of the component.

Embodiment 9

the method of embodiment 7, wherein the plurality of active sensors are arranged in a grid pattern over a cross section of the component.

Embodiment 10

the method of embodiment 9, wherein detecting the condition of flow includes detecting an instantaneous phase fraction based upon the determined phase of the at least one medium at each of the plurality of active sensors and the location of each of the plurality of active sensors within the component.

Embodiment 11

the method of embodiment 9 or 10, wherein detecting the condition of flow includes detecting flow regime based upon the determined phase of the at least one medium at each of the plurality of active sensors over time and the location of each of the plurality of active sensors within the component.

Embodiment 12

the method of embodiment 10 or 11, wherein the second sensing cable further includes a passive fiber optic sensor array having a plurality passive sensors, the method further comprising: measuring, over time, a temperature profile of the second sensing cable each of the plurality of passive sensors corresponding to the heat pulse; and determining a flow velocity of the one or more media flowing through the component at each of the plurality of active sensors by correlating the temperature profile of each of the active sensors with the temperature profile of at least a respective one of the passive sensors.

Embodiment 13

the method of embodiment 12, wherein detecting the condition of flow further includes detecting a volumetric and mass flow rate of each phase of the instantaneous phase fraction of the one or more media based upon the determined flow velocity at each of the plurality of active sensors, the determined phase of the at least one medium at each of the plurality of active sensors, and the location of each of the plurality of active sensors within the component.

Embodiment 14

a system for detecting a condition of multi-phase flow through a component having one or more media flowing therethrough, comprising: a first sensing cable aligned with a heating element and including at least one active optical fiber sensor at a first sensing location within a component; at least a second sensing cable including at least one optical fiber sensor at a second sensing location, the second sensing location being at a predetermined distance from the first sensing location; an excitation source configured to propagate at least one heat pulse through the heating element along at least a portion of the first sensing cable to affect an exchange of thermal energy between the heating element and at least one medium exposed to the sensing cable; an optical signal interrogator coupled with the first sensing cable and the second sensing cable, to measure, over time, a first temperature profile of the first sensing cable at the first sensing location corresponding to the heat pulse, and a second temperature profile of the second sensing cable at the second sensing location corresponding to the heat pulse; a control unit, coupled to the optical signal interrogator, to determine a flow velocity of the one or more media flowing through the component by correlating the first temperature profile with the second temperature profile; and configured to detect a condition of flow of the one or more media by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

Embodiment 15

the system of embodiment 14, wherein the optical signal interrogator is configured to measure the temperature profile corresponding to the heat pulse at the first sensing location by measuring at least a heating temperature measurement during propagation of the heat pulse over the sensor location, a peak temperature measurement, and a cooling temperature measurement after propagation of the heat pulse over the sensor.

Embodiment 16

the system of embodiment 14 or 15, wherein the optical signal interrogator is configured to measure the temperature profile corresponding to the heat pulse at the first sensing location by measuring a plurality of temperatures over a period of time upon arrival of the heat pulse at the sensor location.

Embodiment 17

the system of embodiment 16, wherein the control unit is configured to determine the phase of the medium exposed to the sensing cable at the first sensing location by performing a regression of the plurality of temperatures over a logarithm of corresponding measurement times for a predetermined time window in the period of time to generate a slope and an intercept of the regression, wherein the slope and the intercept relate to the phase of the medium exposed to the sensing cable at the first sensing location.

Embodiment 18

the system of embodiment 16 or 17, wherein the control unit is configured to determine the phase of the medium exposed to the sensing cable at the first sensing location by: generating a time derivative by calculating a derivative of the plurality of temperature measurements with respect to time; applying a transform to the time derivative to generate a complex spectrum; and determining an amplitude and a phase of the complex spectrum, wherein the amplitude and the phase of the complex spectrum relate to the phase of the medium exposed to the sensing cable at first sensing location.

Embodiment 19

the system of embodiment 18, wherein the control unit is configured to determine the phase of the medium exposed to the sensing cable at the first sensing location by further: generating a frequency derivative spectrum by calculating the derivative of the complex spectrum with respect to frequency; and determining an amplitude and a phase of the frequency derivative spectrum, wherein the amplitude and the phase of the frequency derivative spectrum relate to the phase of the medium exposed to the sensing cable at the first sensing location.

Embodiment 20

the system of embodiment 14, 15, 16, 17, 18 or 19, wherein the first sensing cable includes an active fiber optic sensor array having a plurality of active sensors, each active sensor having a location within the component; wherein the optical signal interrogator is further configured to measure, over time, a temperature profile of the first sensing cable at each of the plurality of active sensors corresponding to the heat pulse; and wherein the control unit is further configured to detect the condition of flow further by determining the phase of the at least one medium exposed to the sensing cable at each of the plurality of active sensors based on the corresponding temperature profile and the determined flow velocity.

Embodiment 21

the system of embodiment 20, wherein the plurality of active sensors are arranged circumferentially along a perimeter of a wall of the component.

Embodiment 22

the system of embodiment 20 or 21, wherein the plurality of active sensors are arranged in a grid pattern over a cross section of the component.

Embodiment 23

the system of embodiment 22, wherein the control unit is further configured to detect the condition of flow by detecting an instantaneous phase fraction based upon the determined phase of the at least one medium at each of the plurality of active sensors and the location of each of the plurality of active sensors within the component.

Embodiment 24

the system of embodiment 22 or 23, wherein the control unit is further configured to detect the condition of flow by detecting flow regime based upon the determined phase of the at least one medium at each of the plurality of active sensors over time and the location of each of the plurality of active sensors within the component.

Embodiment 25

the system of embodiment 23 or 24, wherein the second sensing cable further includes a passive fiber optic sensor array having a plurality passive sensors; wherein the optical signal interrogator is further configured to measure, over time, a temperature profile of the second sensing cable each of the plurality of passive sensors corresponding to the heat pulse; and wherein the control unit is further configured to determine a flow velocity of the one or more media flowing through the component at each of the plurality of active sensors by correlating the temperature profile of at least a respective one of the active sensors with the temperature profile of each of the passive sensors.

Embodiment 26

the system of embodiment 25, wherein the control unit is further configured to detect the condition of flow by detecting a volumetric and mass flow rate of each phase of the instantaneous phase fraction of the one or more media based upon the determined flow velocity at each of the plurality of active sensors, the determined phase of the at least one medium at each of the plurality of active sensors, and the location of each of the plurality of active sensors within the component.

While the disclosed subject matter is described herein in terms of certain exemplary embodiments, those skilled in the art will recognize that various modifications and improvements can be made to the disclosed subject matter without departing from the scope thereof. Moreover, although individual features of one embodiment of the disclosed subject matter can be discussed herein or shown in the drawings of the one embodiment and not in other embodiments, it should be apparent that individual features of one embodiment can be combined with one or more features of another embodiment or features from a plurality of embodiments.

In addition to the specific embodiments claimed below, the disclosed subject matter is also directed to other embodiments having any other possible combination of the dependent features claimed below and those disclosed above. As such, the particular features presented in the dependent claims and disclosed above can be combined with each other in other manners within the scope of the disclosed subject matter such that the disclosed subject matter should be recognized as also specifically directed to other embodiments having any other possible combinations. Thus, the foregoing description of specific embodiments of the disclosed subject matter has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the disclosed subject matter to those embodiments disclosed.

It will be apparent to those skilled in the art that various modifications and variations can be made in the method and system of the disclosed subject matter without departing from the spirit or scope of the disclosed subject matter. Thus, it is intended that the disclosed subject matter include modifications and variations that are within the scope of the appended claims and their equivalents.

The invention claimed is:

1. A method for detecting a condition of multi-phase flow through a component having one or more media flowing therethrough, comprising:

providing within the component a first sensing cable aligned with a heating element and including at least one active optical fiber sensor at a first sensing location;

providing within the component at least a second sensing cable including at least one optical fiber sensor at a second sensing location, the second sensing location being at a predetermined distance from the first sensing location;

propagating at least one heat pulse through the heating element along at least a portion of the first sensing cable to affect an exchange of thermal energy between the heating element and at least one medium exposed to the sensing cable;

measuring, over time, a first temperature profile of the first sensing cable at the first sensing location corresponding to the heat pulse;

measuring, over time, a second temperature profile of the second sensing cable at the second sensing location corresponding to the heat pulse;

determining a flow velocity of the one or more media flowing through the component by correlating the first temperature profile with the second temperature profile; and

detecting a condition of flow of the one or more media by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

2. The method of claim 1, wherein measuring the temperature profile corresponding to the heat pulse at the first sensing location includes measuring at least a heating temperature measurement during propagation of the heat pulse over the sensor location, a peak temperature measurement, and a cooling temperature measurement after propagation of the heat pulse over the sensor.

3. The method of claim 1, wherein measuring the temperature profile corresponding to the heat pulse at the first sensing location includes measuring a plurality of temperatures over a period of time upon arrival of the heat pulse at the sensor location.

4. The method of claim 3, wherein determining the phase of the medium exposed to the sensing cable at the first sensing location includes performing a regression of the plurality of temperatures over a logarithm of corresponding measurement times for a predetermined time window in the period of time to generate a slope and an intercept of the regression, wherein the slope and the intercept relate to the phase of the medium exposed to the sensing cable at the first sensing location.

5. The method of claim 3, wherein determining the phase of the medium exposed to the sensing cable at the first sensing location includes:

generating a time derivative by calculating a derivative of the plurality of temperature measurements with respect to time;

applying a transform to the time derivative to generate a complex spectrum; and

determining an amplitude and a phase of the complex spectrum, wherein the amplitude and the phase of the complex spectrum relate to the phase of the medium exposed to the sensing cable at first sensing location.

6. The method of claim 5, wherein determining the phase of the media exposed to the sensing cable at the first sensing location further includes:

generating a frequency derivative spectrum by calculating the derivative of the complex spectrum with respect to frequency; and

determining an amplitude and a phase of the frequency derivative spectrum, wherein the amplitude and the phase of the frequency derivative spectrum relate to the phase of the medium exposed to the sensing cable at the first sensing location.

7. The method of claim 1, wherein the first sensing cable includes an active fiber optic sensor array having a plurality of active sensors, each active sensor having a location within the component, the method further comprising:

measuring, over time, a temperature profile of the first sensing cable at each of the plurality of active sensors corresponding to the heat pulse; and

wherein detecting the condition of flow further comprises determining the phase of the at least one medium exposed to the sensing cable at each of the plurality of active sensors based on the corresponding temperature profile and the determined flow velocity.

8. The method of claim 7, wherein the plurality of active sensors are arranged circumferentially along a perimeter of a wall of the component.

9. The method of claim 7, wherein the plurality of active sensors are arranged in a grid pattern over a cross section of the component.

10. The method of claim 9, wherein detecting the condition of flow includes detecting an instantaneous phase fraction based upon the determined phase of the at least one medium at each of the plurality of active sensors and the location of each of the plurality of active sensors within the component.

11. The method of claim 9, wherein detecting the condition of flow includes detecting flow regime based upon the determined phase of the at least one medium at each of the plurality of active sensors over time and the location of each of the plurality of active sensors within the component.

12. The method of claim 10, wherein the second sensing cable further includes a passive fiber optic sensor array having a plurality passive sensors, the method further comprising:

measuring, over time, a temperature profile of the second sensing cable each of the plurality of passive sensors corresponding to the heat pulse; and

determining a flow velocity of the one or more media flowing through the component at each of the plurality of active sensors by correlating the temperature profile of each of the active sensors with the temperature profile of at least a respective one of the passive sensors.

13. The method of claim 12, wherein detecting the condition of flow further includes detecting a volumetric and mass flow rate of each phase of the instantaneous phase fraction of the one or more media based upon the determined flow velocity at each of the plurality of active sensors, the determined phase of the at least one medium at each of the plurality of active sensors, and the location of each of the plurality of active sensors within the component.

14. A system for detecting a condition of multi-phase flow through a component having one or more media flowing therethrough, comprising:

a first sensing cable aligned with a heating element and including at least one active optical fiber sensor at a first sensing location within the component;

at least a second sensing cable including at least one optical fiber sensor at a second sensing location, the second sensing location being at a predetermined distance from the first sensing location;

an excitation source configured to propagate at least one heat pulse through the heating element along at least a portion of the first sensing cable to affect an exchange of thermal energy between the heating element and at least one medium exposed to the sensing cable;

an optical signal interrogator coupled with the first sensing cable and the second sensing cable, to measure, over time, a first temperature profile of the first sensing cable at the first sensing location corresponding to the heat pulse, and a second temperature profile of the second sensing cable at the second sensing location corresponding to the heat pulse;

a control unit, coupled to the optical signal interrogator, to determine a flow velocity of the one or more media flowing through the component by correlating the first temperature profile with the second temperature profile; and configured to detect a condition of flow of the one or more media by determining a phase of the at least one medium exposed to the sensing cable at the first sensing location based on the first temperature profile and the determined flow velocity.

15. The system of claim **14**, wherein the optical signal interrogator is configured to measure the temperature profile corresponding to the heat pulse at the first sensing location by measuring at least a heating temperature measurement during propagation of the heat pulse over the sensor location, a peak temperature measurement, and a cooling temperature measurement after propagation of the heat pulse over the sensor.

16. The system of claim **14**, wherein the optical signal interrogator is configured to measure the temperature profile corresponding to the heat pulse at the first sensing location by measuring a plurality of temperatures over a period of time upon arrival of the heat pulse at the sensor location.

17. The system of claim **16**, wherein the control unit is configured to determine the phase of the medium exposed to the sensing cable at the first sensing location by performing a regression of the plurality of temperatures over a logarithm of corresponding measurement times for a predetermined time window in the period of time to generate a slope and an intercept of the regression, wherein the slope and the intercept relate to the phase of the medium exposed to the sensing cable at the first sensing location.

18. The system of claim **16**, wherein the control unit is configured to determine the phase of the medium exposed to the sensing cable at the first sensing location by:

generating a time derivative by calculating a derivative of the plurality of temperature measurements with respect to time;

applying a transform to the time derivative to generate a complex spectrum; and

determining an amplitude and a phase of the complex spectrum, wherein the amplitude and the phase of the complex spectrum relate to the phase of the medium exposed to the sensing cable at first sensing location.

19. The system of claim **18**, wherein the control unit is configured to determine the phase of the medium exposed to the sensing cable at the first sensing location by further:

generating a frequency derivative spectrum by calculating the derivative of the complex spectrum with respect to frequency; and

determining an amplitude and a phase of the frequency derivative spectrum, wherein the amplitude and the phase of the frequency derivative spectrum relate to the phase of the medium exposed to the sensing cable at the first sensing location.

20. The system of claim **14**, wherein the first sensing cable includes an active fiber optic sensor array having a plurality of active sensors, each active sensor having a location within the component;

wherein the optical signal interrogator is further configured to measure, over time, a temperature profile of the first sensing cable at each of the plurality of active sensors corresponding to the heat pulse; and

wherein the control unit is further configured to detect the condition of flow further by determining the phase of the at least one medium exposed to the sensing cable at each of the plurality of active sensors based on the corresponding temperature profile and the determined flow velocity.

21. The system of claim **20**, wherein the plurality of active sensors are arranged circumferentially along a perimeter of a wall of the component.

22. The system of claim **20**, wherein the plurality of active sensors are arranged in a grid pattern over a cross section of the component.

23. The system of claim **22**, wherein the control unit is further configured to detect the condition of flow by detecting an instantaneous phase fraction based upon the determined phase of the at least one medium at each of the plurality of active sensors and the location of each of the plurality of active sensors within the component.

24. The system of claim **22**, wherein the control unit is further configured to detect the condition of flow by detecting flow regime based upon the determined phase of the at least one medium at each of the plurality of active sensors over time and the location of each of the plurality of active sensors within the component.

25. The system of claim **23**, wherein the second sensing cable further includes a passive fiber optic sensor array having a plurality passive sensors;

wherein the optical signal interrogator is further configured to measure, over time, a temperature profile of the second sensing cable each of the plurality of passive sensors corresponding to the heat pulse; and

wherein the control unit is further configured to determine a flow velocity of the one or more media flowing through the component at each of the plurality of active sensors by correlating the temperature profile of at least a respective one of the active sensors with the temperature profile of each of the passive sensors.

26. The system of claim **25**, wherein the control unit is further configured to detect the condition of flow by detecting a volumetric and mass flow rate of each phase of the instantaneous phase fraction of the one or more media based upon the determined flow velocity at each of the plurality of active sensors, the determined phase of the at least one medium at each of the plurality of active sensors, and the location of each of the plurality of active sensors within the component.

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